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ALTITUDE EVALUATION OF SEVERAL AFTERBURNER DESIGN
VARIABLES ON A J47-GE-17 TURBOJET ENGINEBy Willis M. Braithwaite, Curtis L. Walker
and Joseph N. SivoLewis Flight Propulsion Laboratory
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUMALTITUDE EVALUATION OF SEVERAL AFTERBURNER DESIGN VARIABLES
ON A J47-GE-17 TURBOJET ENGINEBy Willis M. Braithwaite, Curtis L. Walker,
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SUMMARY

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An investigation was conducted in an NACA altitude chamber to evaluate the effectiveness of turbine-outlet gas-straightening vanes and vortex generators, fuel distribution modifications, and afterburner shell cooling as means of improving afterburner performance. Installation of the turbine-outlet gas-straightening vanes and vortex generators resulted in a lower total-pressure loss through the afterburner and an altered air-flow profile at the afterburner inlet. Therefore, it was necessary to modify the fuel distribution to provide a good fuel-air environment at the flame holder. Another result of the installation of the turbine-outlet gas-straightening vanes and vortex generators was the reduction of the afterburner shell temperature by approximately 100° R. An additional 100° R reduction in the afterburner shell temperature was obtained with a ceramic-coated corrugated liner.

The best afterburner configuration of this investigation incorporated the turbine-outlet gas-straightening vanes and vortex generators, the ceramic-coated corrugated liner, and a fuel distribution that provided a good fuel-air environment at the flame holder. This configuration had higher afterburner combustion efficiencies than the original configuration, and the altitude limit was in excess of 54,000 feet. At low altitudes, the operation of this configuration was not limited by afterburner shell temperatures.

INTRODUCTION

Current and proposed military aircraft require thrust in addition to normal engine thrust for take-off, climb, and high speed at high altitudes. Using an afterburner is one method of meeting these require-

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ments for additional thrust. Accordingly, the NACA is actively conducting several related afterburner programs.

The investigation reported herein presents information on design factors and modifications of the production afterburner for the J47-GE-17 turbojet engine designed for medium temperature operation. The present report is concerned only with the afterburner performance and operating characteristics. Altitude-starting characteristics of two of the configurations in this report are discussed in reference 1. This investigation was conducted with an engine equipped with a variable-area exhaust nozzle and operated over a range of simulated flight conditions in a 10-foot-diameter altitude test chamber at the NACA Lewis laboratory.

The initial configuration was developed by the manufacturer from a previous production afterburner by incorporating design modifications indicated by investigations reported in references 2 to 5. In the present investigation, attention was focused on three primary factors in order to improve the performance and operating limits: (1) turbine-outlet gas whirl, (2) matching of the fuel distribution with the mass-flow distribution of the turbine gases, and (3) afterburner shell cooling. Previous investigations (ref. 6) indicate that turbine-outlet gas whirl can have a detrimental effect on the performance characteristics of the afterburner. Accordingly, the effect of turbine-outlet gas-straightening vanes and vortex generators on performance was evaluated in this investigation. Several fuel-spray-bar configurations were also evaluated in order to provide satisfactory matching of the fuel distribution with the mass-flow distribution. It was desirable to evaluate methods of afterburner shell cooling, since maximum thrust can be limited by afterburner shell temperatures. Two methods of cooling the afterburner shell were investigated: (1) the incorporation of a method of fuel distribution that provided a lean fuel-air mixture near the outer shell and (2) installation of a ceramic-coated corrugated liner in the burner section.

The performance with these modifications incorporated is presented over a range of altitudes up to 50,000 feet. Data are presented in tabular and graphical form to show the effects on afterburner performance of turbine-outlet gas-straightening vanes and vortex generators, fuel distribution, and a ceramic-coated corrugated liner and to illustrate the effect of variations in flight conditions on one of the best afterburner configurations.

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APPARATUS AND INSTRUMENTATION

Installation

The engine was installed in an altitude chamber that is 10 feet in diameter and 60 feet long (fig. 1). A honeycomb installed in the chamber upstream of the test section straightened and smoothed the flow of the inlet air. A forward bulkhead, which incorporated a labyrinth seal around the forward end of the engine, separated the engine-inlet air from the exhaust and provided a means of maintaining a pressure difference across the engine. A 14-inch butterfly valve in the forward bulkhead provided cooling air for the engine compartment, and a rear bulkhead prevented recirculation of exhaust gases about the engine. The exhaust gas from the jet nozzle was discharged into an exhaust diffuser to recover some of the kinetic energy of the jet and thus to extend the capacity of the exhaust system. The combustion in the afterburner was observed through a periscope located directly behind the engine.

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Engine

A J47-GE-17 afterburning turbojet engine was used in this investigation. The engine has a static sea-level thrust rating of 5420 pounds without afterburning at the rated engine speed of 7950 rpm and a turbine-discharge temperature of 1760° R for an inlet air temperature of 519° R. At this operating condition, the air flow is 104 pounds per second. The over-all length of the engine and afterburner is approximately 228 inches, and the maximum diameter is 41 inches. The dry weight of the engine and afterburner, including the electronic control and airframe mounted components, is 3553 pounds. The electronic control (described in ref. 1) controls the engine speed by regulating engine fuel flow and controls the turbine-outlet temperature by regulating the exhaust-nozzle area.

Afterburner Assembly

A diagram of the afterburner assembly is shown in figure 2. The following were common to all configurations: conical diffuser, two-ring V flame holder mounted by struts from the inner body, converging conical burning section, and variable-area clamshell exhaust nozzle. The conical inner body, mounted from the outer shell by four tubular rods, contained the fuel manifolds and a depressed flame seat in the downstream end. Fuel was supplied to the afterburner by an air-turbine fuel pump driven by compressor bleed air.

Modifications to the afterburner, which were incorporated in six configurations, are listed in table I. The fuel-distribution patterns and spray-bar designs are presented in figure 3. A photograph of the turbine-outlet gas-straightening vanes and vortex generators is shown in figure 4. The ceramic-coated corrugated liner is shown installed in the afterburner section in figure 5. The ceramic used was National Bureau of Standards number A418, primarily composed of chromium oxide.

The six configurations are grouped as to purposes of the modifications. The first group of modifications was selected to show the effect of straightening vanes on engine and afterburner performance. This group included the manufacturer's original configuration A and configuration B, which was made by incorporating in configuration A straightening vanes and vortex generators at the turbine outlet and a 4-inch shorter fuel mixing length (the radial fuel distribution was equivalent to that of configuration A). The shorter fuel mixing length was a result of moving the spray bars downstream of the inner-cone supporting struts to allow equidistant circumferential spacing of the bars.

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The second group of configurations was selected to illustrate the effect of modified fuel distribution. These configurations were geometrically similar, all having straightening vanes, vortex generators, and corrugated liners. Configuration C had a radial fuel distribution equivalent to the original configuration A. In configurations D and E, the fuel distribution was modified to compensate for the shift in mass-flow profile caused by the installation of the straightening vanes and vortex generators. This modification was based on the total-pressure profile at the diffuser outlet. The spray bar for configuration D had equally spaced holes of varied diameters, while the bar for configuration E had varied spacing of equally sized holes. The bar for configuration E, designed by the manufacturer, was a uniorifice bar with a metering orifice at the inlet to the bar that permitted the use of larger spray holes to prevent plugging by foreign material in the fuel.

The third group of modifications was selected to evaluate several methods of cooling the outer shell. Configurations A, B, C, and F are compared. Configuration A was the original configuration already described. Configuration F had a fuel distribution that was lean near the outer shell but was otherwise the same as configuration A. Configuration B differed from configuration A in that turbine-outlet gas-straightening vanes and vortex generators were added, and configuration C differed from configuration B only by the addition of the corrugated liner.

Instrumentation

Engine-inlet air flow was determined by pressure and temperature measurements at the compressor inlet (station 1, fig. 6(a)). Instrumen-

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tation measured the engine midframe air bleed, which was subtracted from the engine-inlet air flow in order to obtain the afterburner air flow. Turbine-outlet temperature was calculated from engine performance, and turbine-outlet temperature for the electronic control was determined by averaging the engine manufacturer's eight thermocouples. The angle of whirl of the gas flow was measured at the diffuser outlet by means of a rotatable rake (fig. 6(b)). Twenty-five thermocouples attached to the afterburner shell measured temperatures at station 8, located $79\frac{5}{8}$ inches downstream of the turbine-outlet flange (fig. 6(c)). Total pressures at the exhaust-nozzle inlet were obtained with a water-cooled survey rake (fig. 6(d)), and ambient pressure in the region of the exhaust-nozzle outlet was determined by static-pressure probes in the plane of the exhaust nozzle. Engine and afterburner fuel flows were measured by calibrated rotameters. The fuel used in this investigation was MIL-F-5624A grade JP-4.

PROCEDURE

The inlet and exhaust conditions for these tests were determined by the altitude and flight Mach number according to NACA standard atmosphere; 100-percent ram pressure recovery was assumed. Afterburner performance data were obtained over a range of altitudes from 15,000 to 50,000 feet at a flight Mach number of 0.6 and a range of flight Mach numbers from 0.4 to 1.0 at an altitude of 30,000 feet. For each flight condition, data were obtained at rated engine speed and turbine-outlet temperature as maintained by the electronic integral control for a range of fuel-air ratios.

The range of fuel-air ratios at each flight condition represents, in general, the practical operating range for the afterburner. The rich operating limit was determined by afterburner shell temperature limit (2010° R) or by maximum nozzle opening. It should be noted that, with the electronic control, exhaust-nozzle area is a function of exhaust-gas temperature. Therefore, maximum nozzle opening was either the physical limit of the nozzle or the area obtained with maximum temperature for those configurations that reached a point of decreasing temperature with increasing fuel flow. The lean limit of operation was indicated by unsteady (oscillatory) combustion in the afterburner or blow-out of the flame. Over the range of conditions investigated (turbine-outlet pressures up to 2950 lb/sq ft with fuel-air ratios up to 0.04), this unsteady combustion at the lean limit was the only oscillatory combustion phenomenon encountered. No significant altitude limits were obtained for these configurations because of limitations of the altitude exhaust facilities. For afterburning conditions, the facility was limited to about 54,000 feet, which corresponds to a turbine-outlet total pressure of about 580 pounds per square foot.

The jet thrust produced by the engine and afterburner was measured by a self-balancing null-type pneumatic thrust cell. A sketch of the linkage from the engine to the thrust cell is presented in figure 1(b). The symbols and methods of calculation are presented in the appendix.

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RESULTS AND DISCUSSION

The results of this investigation are discussed in relation to the three factors considered for improving the afterburner performance; that is, (1) reduction of whirl in the turbine-outlet gas, (2) matching of the fuel distribution with the mass-flow distribution, and (3) cooling of the afterburner shell. The altitude performance data are presented in tabular form in table II and in graphical form in figures 7 to 17.

Effects of Turbine-Outlet Gas-Straightening Vanes and Vortex Generators on Afterburner Performance

The performance of an afterburning engine may be detrimentally affected by high angle of whirl of the turbine-outlet gases (ref. 6). The addition of a whirl velocity produces high resultant velocities that make burning more difficult. Furthermore, a high angle of whirl produces high total-pressure losses in the burner that are particularly noticeable during nonafterburning operation. Whirl losses are less pronounced during combustion, probably because the high level of turbulence during combustion reduces the whirl component of the flow.

Since whirl angle increases with diffusion (ref. 7), measurements of the whirl were made at the diffuser outlet to obtain the maximum angle and the results are presented in figure 7. The method of obtaining this curve is the same as used in reference 6. The direction of whirl was opposite to turbine rotation, as indicated by the negative angles on figure 7, and was greater than 30° over most of the passage. The installation of the turbine-outlet gas-straightening vanes and vortex generators, designed by the manufacturer to reduce the whirl angle and to provide a uniform velocity profile, resulted in only 10° whirl in the same counterrotational direction.

Effect on afterburner-inlet temperature and pressure profiles. - Installation of the turbine-outlet gas-straightening vanes and vortex generators caused a shift in afterburner-inlet temperature profile in relation to the control thermocouple. After the vanes and vortex generators were installed, the average burner-inlet gas temperature was from 40° to 70° R lower for the same indicated control temperature.

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This effect can be seen by inspection of data from table II. The setting of turbine-outlet temperature with the manufacturer's instrumentation resulted in operation at a lower turbine-outlet temperature and resulting lower nonafterburning thrusts for the configurations having straightening vanes and vortex generators.

Another effect of the straightening vanes and vortex generators was a slightly more uniform total-pressure distribution (fig. 8) at the diffuser-outlet (station 6). This trend in total-pressure profile indicates more nearly uniform mass-flow and velocity distribution of the combustion gases. However, a comparison of the pressure levels on figure 8 is invalid because of the different temperature levels.

Effect on internal performance. - A comparison of the total-pressure-loss ratios before and after the straightening vanes and vortex generators were installed is presented in figure 9. In the configuration with vanes and vortex generators (configuration B), the turbine-outlet total-pressure measurements were made downstream of the vanes. Therefore, the total-pressure loss through the straightening vanes and vortex generators was not included in the pressure-loss ratio, defined as the ratio of the total-pressure loss through the burner to the burner-inlet total pressure. The pressure-loss ratio through the vanes and vortex generators was determined to be approximately 0.025 at 30,000 feet and 0.035 at 50,000 feet from the engine pumping characteristics. This value has been added to the data on figure 9 for configuration B, and the combined pressure loss is shown by the dashed curve. Thus the installation of the straightening vanes and vortex generators reduced the over-all pressure-loss ratio by 0.02 to 0.01, the greater reduction occurring at low fuel-air ratios where the whirl is believed to have been greater.

The afterburner combustion efficiencies before (configuration A) and after (configuration B) straightening vanes and vortex generators were installed are compared in figure 10(a). For the range of fuel-air ratios investigated there was no appreciable difference in combustion efficiency at 30,000 feet, while at 50,000 feet the configuration with vanes and vortex generators had lower combustion efficiency. This loss in efficiency with vanes was due to a poor fuel-air distribution. The fuel distribution was designed for the mass-flow profile that existed before the vanes were installed. Following installation of the vanes, this mass-flow profile was modified, but the fuel distribution remained the same and resulted in a different fuel-air ratio profile.

The decrease in combustion efficiency for configuration B at 50,000 feet resulted in lower exhaust-gas temperatures (fig. 10(b)). The lower turbine-outlet temperatures also contributed to the decrease in afterburner exhaust-gas temperature.

Effect on over-all performance. - As previously noted, the effect of the straightening vanes and vortex generators was to reduce the afterburner pressure loss, and an increase in thrust would be expected. However, because of the difference in turbine-outlet conditions in this investigation, the increase in thrust was not realized and the augmented jet thrust ratio was the only valid basis for thrust comparison. (The nonafterburning jet thrust was calculated for each point with the turbine-outlet conditions obtained at that point and with the pressure drop assumed through a standard tail pipe as explained in the appendix.) The augmented jet thrust ratios are presented in figure 10(c). At 30,000 feet, where combustion efficiency was essentially the same, installation of the straightening vanes and vortex generators resulted in an increased jet thrust ratio of about 0.03. At 50,000 feet, however, the reduction in combustion efficiency countered the reduction in afterburner pressure loss, and an increase of only 0.01 was observed in jet thrust ratio.

Net thrust specific fuel consumption, presented in figure 10(d), is affected by the tail-pipe pressure loss, turbine-outlet gas temperature, and combustion efficiency. At 30,000 feet, combustion efficiency was unaffected by the turbine-outlet gas-straightening vanes, and the reduced tail-pipe pressure loss should have resulted in decreased specific fuel consumption. However, the lack of improvement illustrates the fact that the control should be rescheduled to give the same engine operating conditions after the temperature profile shift due to the installation of the straightening vanes. Also, the shift in mass-flow profile due to the addition of the vanes required an alteration to the fuel distribution to prevent a decrease in combustion efficiency at 50,000 feet. The results of modifying the fuel distribution after straightening vanes and vortex generators were installed are discussed in the following section.

Effect of Fuel Distribution on Performance

The installation of the turbine-outlet straightening vanes and vortex generators resulted in a loss in combustion efficiency that was attributed to a poor fuel-air distribution. Before alteration of the fuel system, a ceramic-coated corrugated liner was installed, the effects of which will be discussed later. Configurations C, D, and E differed only in fuel distribution.

A comparison of the combustion efficiency of configuration C, which had a fuel distribution equivalent to the original configuration

A, and configuration D, which had a fuel distribution designed to match the mass-flow profile, is presented in figure 11(a). The peak efficiency of configuration D occurred at higher fuel-air ratios than it did for configuration C. Also, configuration D had about 0.11 higher combustion efficiency than configuration C at 50,000 feet. For example, at 50,000 feet, combustion efficiency for configuration D had a peak value of 0.82 at a fuel-air ratio of 0.037 and was about 0.70 at a fuel-air ratio of 0.06.

The exhaust-gas temperature (fig. 11(b)) and net thrust ratio (fig. 11(c)) were higher for configuration D above a fuel-air ratio of 0.035 at 30,000 and 40,000 feet and higher at all fuel-air ratios investigated at 50,000 feet. Net thrust specific fuel consumption (fig. 11(d)) was lower for configuration D above a fuel-air ratio of 0.035 at 30,000 and 40,000 feet and lower at all fuel-air ratios investigated at 50,000 feet. The redesigned fuel distribution provided an improvement in combustion efficiency at fuel-air ratios in excess of 0.035 and, hence, in over-all afterburner performance.

Comparison of configurations D and E (figs. 11(a) to (c)) shows that the use of equal-diameter spray holes with various spacing (configuration E) resulted in about the same performance as with various-diameter spray holes with equal spacing (configuration D). Furthermore, the use of a metering orifice at the inlet to the spray bar did not affect performance.

Afterburner Shell Cooling

A maximum temperature limit of 2010° R for the afterburner shell was imposed by the structural strength requirements of the afterburner. The shell temperature of an afterburner is a function of the exhaust-gas temperature and the burner pressure (gas density). It was found that with a rich fuel-air mixture the original configuration A was limited at 30,000 feet and below by maximum shell temperature. Therefore, to permit higher exhaust-gas temperatures at low altitudes, methods of cooling the afterburner shell were investigated.

Reduction in turbine-outlet whirl. - A reduction in the temperature of the afterburner shell of from 80° to 120° R resulted from the installation of the straightening vanes and vortex generators (fig. 12) at an exhaust-gas temperature of 3100° R and altitudes of 30,000 and 50,000 feet. The larger reduction occurred at the lower altitude, where shell cooling was more critical. The data further indicate that the reduction would have been greater at higher fuel-air ratios. This decrease in shell temperature with the installation of straightening vanes was due to two factors. The decrease in whirl reduced the

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tendency for the fuel to centrifuge toward the outer shell and also probably increased the thickness of the boundary layer at the outer shell.

Fuel distribution moved away from shell. - A previous investigation (ref. 5) showed that shell temperatures could be lowered by modifying the fuel distribution to reduce the amount of burning near the shell. Configuration F incorporates such a modification, as shown by a comparison of figures 3(a) and (e). This modification reduced the shell temperature approximately 30° at 30,000 feet (fig. 12). However, it lowered the altitude limit from over 54,000 feet for configuration A to 50,000 feet for configuration F at a flight Mach number of 0.6. 2837

Ceramic-coated corrugated liner. - Configuration C incorporated a ceramic-coated corrugated liner installed in the afterburner in addition to the straightening vanes and vortex generators. Over the range of exhaust-gas temperatures investigated, the combination of straightening vanes and liner reduced the temperature 200° to 300° R. For configuration C an increase in exhaust-gas temperature from 2800° to 3300° R at 30,000 feet (fig. 12(b)) resulted in only 50° R increase in shell temperature. The combination of straightening vanes and liner was the most effective means of reducing shell temperatures investigated and was equivalent to the use of approximately 8 percent of engine air flow for cooling air in a conventional convective cooling system.

The coating used on the liner was a Bureau of Standards number A418 ceramic. After approximately 33 hours of afterburning, the coating and liner showed no evidence of deterioration.

A comparison of the shell temperatures for the three configurations (A, B, and C) over a range of turbine-outlet pressures with an exhaust-gas temperature of 3100° R is presented in figure 13. The temperature for the original configuration A increased with increasing pressure, while that for configuration C (liner plus straightening vanes and vortex generators) was essentially constant. This figure illustrates the greater effectiveness of the vanes and liner at low altitudes (high burner pressures), where shell temperatures were found to be critical on the original configuration.

Performance of Final Configuration

Performance data are presented for configuration D over a range of altitudes from 15,000 to 50,000 feet at a flight Mach number of 0.6, and for flight Mach numbers of 0.4 and 0.8 at an altitude of 30,000

feet. This configuration was used for evaluation because it had performance and operating and cooling characteristics equivalent or superior to any of the other configurations.

Effect of altitude and flight Mach number variations. - For a given afterburner fuel-air ratio, increasing the altitude at a constant flight Mach number tended to lower the combustion efficiency, exhaust-gas temperature, and augmented net thrust ratio (fig. 14). The peak combustion efficiency decreased from 96 percent for an afterburner fuel-air ratio of 0.027 at 15,000 feet to 82 percent for a fuel-air ratio of 0.037 at 50,000 feet. The corresponding exhaust-gas temperatures were 2960° and 2880° R. For a constant fuel-air ratio of 0.03, the temperature decreased from 2960° R at 15,000 feet to 2710° R at 50,000 feet, while the combustion efficiency decreased from 96 to 76 percent. For a wide-open exhaust nozzle, the exhaust-gas temperature decreased from 3550° R at 30,000 feet at a fuel-air ratio of 0.056 (high temperature data were not obtained at 15,000 ft) to 3380° R at 50,000 feet at a fuel-air ratio of 0.061. This decrease resulted in a decrease in augmented net thrust ratio from 1.6 to 1.52.

The net thrust specific fuel consumption decreased as the altitude increased up to an altitude between 30,000 and 40,000 feet. A further increase in altitude resulted in an increase in specific fuel consumption. This decrease was due to the increasing engine cycle efficiency with the decreasing compressor-inlet temperature as the altitude increased until the tropopause (35,000 ft) was reached, which more than compensated for the decrease in combustion efficiency. Above the tropopause, the temperature remained constant, and the decreasing combustion efficiency caused an increase in specific fuel consumption.

The effect of varying flight Mach number at an altitude of 30,000 feet is presented in figure 15. A decrease in flight Mach number affected the afterburner combustion efficiency (fig. 15(a)) and the exhaust-gas temperature (fig. 15(b)) in the same manner as did an increase in altitude; that is, combustion efficiency and exhaust-gas temperature decreased with decreasing Mach number for a given afterburner fuel-air ratio. However, since the range of flight Mach numbers was small (0.8 to 0.4), the effect was slight. The augmented net thrust ratio (fig. 15(c)) decreased with decreasing Mach number, but the net thrust specific fuel consumption (fig. 15(d)) increased as a result of the decreasing combustion efficiency.

Afterburner combustion efficiency as a function of turbine-outlet total pressure is presented in figure 16 for afterburner fuel-air ratios of 0.025, 0.035, 0.045, and 0.055. At the low fuel-air ratio, the efficiency decreased rapidly with decreasing pressure, but decreasing pressure affected the efficiency less at the higher fuel-air ratios.

Thrust Generalization

A method of generalizing jet thrust for a turbojet engine has been developed in reference 8. The basis of this method is that the jet thrust is a function of the flow through a nozzle and may, therefore, be described in terms of the nozzle-inlet total pressure, the ambient static pressure, and the throat area of the nozzle. If the experimentally determined jet thrust is adjusted for nozzle area variation, it will generalize when plotted against $(1.25P_g - p_0)$. This method of generalization provides a calibration that may be used in determining turbojet engine jet thrust in a flight installation for take-off and flight conditions.

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This method of generalizing jet thrust has been used for the data of configuration D (fig. 17). The factor used to adjust the jet thrust for area variations of the variable-area nozzle, which is presented in figure 17(b), is the ratio of jet thrust to jet thrust for maximum nozzle area as a function of the ratio of actual nozzle area to maximum nozzle area. Therefore, the jet thrust presented in figure 17(a) is the jet thrust obtainable with the maximum nozzle area.

The generalized thrust curve may be used to obtain the jet thrust for a given flight condition and afterburner fuel-air ratio. The values of the exhaust-nozzle-inlet total pressure and ambient static pressure may be obtained from the flight conditions and the engine characteristics. With these data, the jet thrust for maximum nozzle area can be obtained. The exhaust-nozzle area for a given afterburner fuel-air ratio can be obtained from figure 17(c), and from this the ratio of jet thrust at the given exhaust-nozzle area to the jet thrust at maximum nozzle area can be obtained. A numerical example of this calculation is given in the appendix.

CONCLUDING REMARKS

An investigation of the J47-GE-17 afterburning engine showed that the installation of turbine-outlet gas-straightening vanes and vortex generators reduced the counterrotational whirl by approximately 20° . This change modified the burner-inlet (turbine-outlet) total-temperature profile so that the calculated average turbine-outlet gas temperature was from 40° to 70° R lower for the same indicated control temperature. This decrease in turbine-outlet temperature resulted in lower thrust for the same afterburner fuel-air ratio. However, the total-pressure-loss ratio was reduced by 0.01 to 0.02, and the augmented jet thrust ratio was increased by 0.01 to 0.03. Because of a change in total-pressure profile and thus a change in mass-flow profile with the same fuel distribution, the fuel-air distribution

at the flame holder was not as suitable with the vanes and vortex generators, and the combustion efficiency decreased.

By adjusting the fuel distribution to the mass-flow profile that resulted from the installation of the straightening vanes and vortex generators, the loss in combustion efficiency was overcome. The peak value at 50,000 feet altitude was approximately 82 percent at a fuel-air ratio of 0.037 and was about 70 percent at a fuel-air ratio of 0.06. The combustion efficiency, the exhaust-gas temperature, and the augmented net thrust ratio were higher at higher fuel-air ratios, while net thrust specific fuel consumption was lower for the modified fuel distribution. The final fuel distribution was achieved both with spray bars having equally spaced various-diameter holes and uniorifice spray bars having variously spaced equal-diameter holes.

Afterburner shell temperatures were reduced approximately 100° R by the installation of the straightening vanes and vortex generators for an exhaust-gas temperature of 3100° R at 30,000 feet altitude. An additional reduction of 100° R in shell temperature was achieved by the installation of a ceramic-coated corrugated liner. The liner was used for approximately 33 hours of afterburner operation with no noticeable deterioration or change in appearance.

Except at the lean limit of combustion, no oscillatory combustion was encountered during this investigation, which covered burner pressures up to 2950 pounds per square foot with fuel-air ratios up to 0.04.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 18, 1953

APPENDIX - CALCULATIONS

Symbols

The following symbols are used in this report:

A	cross-sectional area, sq ft
C_V	velocity coefficient, ratio of actual jet velocity to effective jet velocity
F_j	jet thrust, lb
F'_j	calculated nonafterburning jet thrust, lb
F_n	net thrust, lb
F'_n	calculated nonafterburning net thrust, lb
f	fuel-air ratio
g	acceleration due to gravity, 32.2 ft/sec^2
h	enthalpy, Btu/lb
h_c	lower heating value of fuel, Btu/lb
M	Mach number
P	total pressure, lb/sq ft abs
P'_9	total pressure at exhaust-nozzle survey station in standard engine tail pipe, lb/sq ft abs
p	static pressure, lb/sq ft abs
R	gas constant, $53.4 \text{ ft-lb/(lb)(}^{\circ}\text{R)}$
T	total temperature, $^{\circ}\text{R}$
V	velocity, ft/sec
V_{ef}	effective velocity, ft/sec
W_a	air flow, lb/sec

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$W_{a,c}$ compressor leakage air flow, lb/sec
 W_f fuel flow, lb/hr
 W_f/F_n specific fuel consumption based on total fuel flow and net thrust, (lb/hr)/lb thrust
 W_g gas flow, lb/sec
 γ ratio of specific heats for gases
 η combustion efficiency

Subscripts:

a air
ab afterburner
e engine
f fuel
g gas
m maximum exhaust-nozzle area
n exhaust-nozzle outlet, vena contracta
nc nozzle cooling
s labyrinth seal
T total
tc turbine cooling
tp turbine pump
0 free-stream conditions
1 engine inlet
3 compressor outlet at engine combustor inlet
5 turbine outlet or tail-pipe diffuser inlet

9 exhaust-nozzle inlet
 10 exhaust-nozzle outlet

Methods of Calculations

Flight Mach number and airspeed. - Flight Mach number and equivalent airspeed were calculated from engine-inlet total pressure and temperature and free-stream static pressure with complete total-pressure ram recovery assumed:

$$M_0 = \sqrt{\frac{2}{\gamma_1 - 1} \left[\left(\frac{P_1}{P_0} \right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1 \right]}$$

and

$$V_0 = M_0 \sqrt{\gamma_1 g R T_1 \left(\frac{P_0}{P_1} \right)^{\frac{\gamma_1 - 1}{\gamma_1}}}$$

Air flow. - Air flow was determined from pressure and temperature measurements obtained in the engine-inlet annulus by the following equation:

$$W_{a,1} = 0.98 p_1 A_1 \sqrt{\frac{2 \gamma_1 g}{(\gamma_1 - 1) R T_1} \left[\left(\frac{P_1}{P_0} \right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1 \right] \left(\frac{P_1}{P_0} \right)^{\frac{\gamma_1 - 1}{\gamma_1}}}$$

where the 0.98 accounts for the 0.02 leakage between measuring station and compressor inlet. Air flow at the compressor outlet (station 3) was obtained by deducting the compressor leakage, turbine and nozzle cooling-air flows, and compressor bleed air used to drive the turbine fuel pump:

$$W_{a,3} = W_{a,1} - W_{a,c} - W_{a,tc} - W_{a,nc} - W_{a,fp}$$

Gas flow. - Afterburner gas flow is

$$W_{g,9} = W_{a,3} + \frac{W_{f,e} + W_{f,ab}}{3600} + W_{a,tc}$$

Fuel-air ratio. - The engine fuel-air ratio is given by the following equation:

$$f_e = \frac{W_{f,e}}{3600 W_{a,3}}$$

The afterburner fuel-air ratio used herein is defined as the weight flow of fuel injected into the afterburner plus the unburned engine fuel divided by the weight flow of unburned air entering the afterburner. By combining air flow, engine fuel flow, afterburner fuel flow, and engine combustion efficiency, the following equation for afterburner fuel-air ratio is obtained:

$$f_{ab} = \frac{(1 - \eta_e)W_{f,e} + W_{f,ab}}{3600(W_{a,3} + W_{a,tc}) - \frac{\eta_e W_{f,e}}{0.0675}}$$

where 0.0675 is the stoichiometric fuel-air ratio for the engine fuel.

The total fuel-air ratio for the engine and afterburner is

$$f = \frac{W_{f,e} + W_{f,ab}}{3600(W_{a,3} + W_{a,tc})}$$

Engine combustor efficiency. - Engine combustor efficiency is the ratio of the enthalpy rise through the engine divided by the product of engine fuel flow and the lower heating value of the fuel:

$$\eta_e = \frac{(h_{a,5} - h_{a,1}) + f_e \lambda_e}{f_e h_c}$$

where $\lambda = \frac{Am + B}{m + 1}$ (symbols of ref. 9).

Engine combustion efficiency was obtained from a correlation of the engine with a standard tail pipe. For this investigation T_5 was then obtained by solving the above equation for $h_{a,5}$.

Afterburner combustion efficiency. - Afterburner combustion efficiency was obtained by dividing the enthalpy rise through the afterburner by the product of the afterburner fuel flow and lower heating value of the fuel:

$$\eta_{ab} = \frac{(h_{a,10} - h_{a,1}) + f \lambda_{10} - \eta_e f_e h_c}{f h_c - \eta_e f_e h_c}$$

Augmented thrust. - The jet thrust of the combined engine and afterburner was determined from the thrust-system measurements by the equation

$$F_j = F_d + A_s (P_1 - p_0) + 0.80 \left(\frac{1}{2} \frac{W_{a,1}}{0.98g} V_0 \right)$$

where F_d is equal to the thrust-system scale reading adjusted for the pressure difference on the link connecting the thrust bed in the test chamber and the measuring cell outside the test chamber, and the last term $0.80 \left(\frac{1}{2} \frac{W_{a,1}}{0.98g} V_0 \right)$ is the difference between the pressure forces on the bellmouth and the momentum at the bellmouth outlet.

The augmented net thrust was obtained by subtracting the free-stream momentum of the inlet air from the jet thrust:

$$F_n = F_j - \frac{W_{a,1}}{0.98g} V_0$$

where the $\frac{W_{a,1}}{0.98}$ is the air flow into the bellmouth.

Nonafterburning jet thrust. - The jet thrust for the nonafterburning engine was calculated for each afterburning point with measured turbine-outlet total pressure, engine gas flow, calculated turbine-outlet total temperature, and an assumed tail-pipe pressure drop. Experimental data from the nonafterburning engine indicated that the total-pressure loss through a standard tail pipe between stations 5 and 9 was approximately 0.04 at rated engine speed, that is, $P_9 = 0.96P_5$. The nozzle velocity coefficient for the nonafterburning engine was assumed to be 0.99, while that for the afterburning engine was assumed to be 0.97. The jet thrust equation used was

$$F'_j = C_V W_{g,5} \sqrt{\frac{RT_5}{g}} \left(\frac{V_{ef}}{\sqrt{gRT}} \right)$$

where (V_{ef}/\sqrt{gRT}) is an effective velocity parameter derived in reference 10; and the nonburning net thrust was

$$F'_n = F'_j - \frac{W_{a,1}}{0.98g} V_0$$

Exhaust-gas total temperature. - The total temperature of the exhaust gas was calculated from the jet thrust and conditions existing at the exhaust nozzle:

$$T_{10} = \frac{1}{C_V^2} \frac{g}{R} \left[\frac{F_j}{W_{g,9}} \frac{1}{\left(\frac{V_{ef}}{\sqrt{gRT}} \right)} \right]^2$$

where $\left(\frac{V_{ef}}{\sqrt{gRT}} \right)$ is the effective velocity parameter.

Calculated jet thrust from generalized jet thrust. - It has been shown (ref. 8) that the jet thrust of a turbojet engine may be related to the nozzle-inlet total pressure, ambient static pressure, and area. This relation is

$$F_j \propto A_{10} (1.25P_9 - p_0)$$

This equation may be represented by two plots as figures 17(a) and (b).

For an assumed flight condition of 40,000 feet altitude and a flight Mach number of 0.6, the pressure values are found from table II as $P_9 = 1009$ pounds per square foot and $p_0 = 392$ pounds per square foot. Then

$$1.25P_9 - p_0 = 1.25(1009) - 392 = 869.5 \text{ lb/sq ft}$$

From figure 17(a), the jet thrust for an open nozzle ($A_{10,m} = 3.5 \text{ sq ft}$), which would require an afterburner fuel-air ratio of 0.0575, is 2790 pounds.

If an afterburner fuel-air of 0.040 is desired,

$$A_{10} = 3.17 \text{ sq ft (from fig. 17(c))}$$

and

$$\frac{A_{10}}{A_{10,m}} = \frac{3.17}{3.50} = 0.906$$

With the area ratio, the thrust correction ratio may be found from figure 17(b) to be

$$F_j/F_{j,m} = 0.912$$

Therefore, the jet thrust for this fuel-air ratio is

$$F_j = F_{j,m} (F_j/F_{j,m}) = 2790(0.912) = 2544 \text{ lb}$$

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TABLE I. - MODIFICATIONS INCORPORATED



Configuration	Number of fuel-spray bars	Orifices per spray bar	Mixing length, in.	Spray-bar location (fig. 2(a))	Fuel distribution (fig. 3)	Modifications
A	19	10	26	1	(a)	Manufacturer's original configuration
B	20	10	22	2	(b)	Fuel distribution equivalent to configuration A; turbine-outlet gas-straightening vanes and vortex generators added
C	20	10	22	2	(b)	Ceramic-coated corrugated liner added to configuration B
D	20	18	22	2	(c)	Modified fuel distribution; other variables same as configuration C; final configuration
E	20	16	22	2	(d)	Uniorifice spray bar with distribution of configuration D; other variables same as configuration C
F	19	10	26	1	(e)	Fuel distribution away from shell; no turbine-outlet straightening vanes, vortex generators, or coated liner

TABLE II. - ALTITUDE

Altitude, ft	Flight Mach number, M_0	Free-stream static pressure, P_0 , lb/sq ft abs	Engine-inlet total pressure, P_1 , lb/sq ft abs	Engine-inlet total temperature, T_1 , °R	Turbine-outlet total pressure, P_5 , lb/sq ft abs	Turbine-outlet total temperature, T_5 , °R	Manufacturer's turbine-outlet control temperature, $T_{5,n}$, °R	Engine-inlet air flow, $w_{a,1}$, lb/sec	Engine fuel flow, $w_{f,e}$, lb/hr	Afterburner fuel flow, $w_{f,ab}$, lb/hr	Total fuel-air ratio, f	Afterburner fuel-air ratio, f_{ab}
Original												
15,000	0.588 .600 .600 .591 .599	1210 1197 1198 1207 1199	1530 1528 1528 1528 1527	547 548 545 550 549	2978 2988 2981 2976 2961	1776 1783 1781 1772 1771	1755 1745 1760 1745 1750	72.50 72.12 72.76 72.24 72.08	4483 4465 4502 4426 4434	7040 5982 5387 4672 4011	0.0452 .0412 .0386 .0368 .0333	0.0374 .0321 .0286 .0249 .0115
30,000	0.587 .581 .583 .581 .583 .581	638 631 633 640 630 631	700 697 700 697 687 697	425 425 425 427 427 426	1814 1806 1803 1811 1806 1804	1805 1770 1770 1790 1786 1770	58.99 58.98 59.04 58.75 58.82 59.91	2690 2668 2688 2650 2672 2680	5303 4391 3629 2980 2408 1974	0.0583 .0217 .0463 .0374 .0413 .0340	0.0446 .0217 .0374 .0309 .0250 .0205	
30,000	0.586 .575 .578 .585 .584 .584	632 640 635 636 628 633	797 801 796 800 798 797	441 441 441 435 440 441	1807 1803 1798 1823 1795 1799	1784 1780 1785 1778 1784 1779	1765 1760 1760 1760 1765 1760	43.60 43.76 43.51 44.00 43.55 43.36	2963 2954 2954 2993 2954 2957	4693 4311 3821 3580 2888 2350	0.0488 .0472 .0351 .0412 .0266 .0346	0.0430 .0392 .0351 .0308 .0216
30,000	0.813 .783 .798 .792 .788 .802	630 633 630 634 637 630	972 959 958 959 959 962	471 468 467 466 466 466	2124 2074 2082 2080 2072 2093	1766 1771 1777 1769 1776 1769	51.15 50.61 50.71 50.79 50.57 50.84	3311 3297 3315 3315 3315 3320	5655 4874 4112 3351 3351 2194	0.0498 .0459 .0416 .0373 .0333 .0308	0.0433 .0379 .0319 .0280 .0204 .0171	
30,000	0.985 .993 .993 .996 .995 .992	639 633 633 631 632 634	1188 1189 1188 1188 1188 1188	497 496 497 494 494 494	2524 2523 2556 2544 2546 2538	1789 1775 1807 1779 1783 1786	1780 1770 1795 1775 1775 1775	60.21 60.75 60.44 60.83 60.80 60.80	3348 3348 4013 3375 3368 3366	4571 4371 4052 3669 3304 2807	0.0402 .0369 .0379 .0357 .0342 .0316	0.0300 .0288 .0266 .0238 .0216 .0184
40,000	0.579 .581 .581 .570 .587 .570 .569	401 397 397 398 393 395 395	503 499 499 496 495 493 492	425 425 425 425 425 425 425	1149 1154 1154 1144 1150 1139 1143	1831 1831 1805 1831 1831 1844 1837	1780 1780 1775 1780 1780 1780 1780	27.77 27.67 28.10 27.53 27.47 27.36 27.38	1960 1852 1945 1945 1945 1952 1945	4473 3765 3284 2754 2512 1941 1558	0.0686 .0689 .0529 .0464 .0441 .0406 .0368	0.0653 .0553 .0470 .0404 .0343 .0292 .0259
50,000	0.643 .628 .643 .630 .609	239 242 239 239 235	315 316 316 312 312	436 433 430 419 421	710 710 711 724 720	1838 1822 1822 1818 1826	1770 1770 1765 1775 1765	16.97 17.13 17.24 17.38 17.30	1218 1221 1226 1240 1243	2807 2610 2261 1901 1672	0.0678 .0619 .0578 .0516 .0482	0.0679 .0622 .0538 .0467 .0401
Configuration B, straightening												
30,000	0.808 .605 .609 .605 .601	822 823 824 823 825	798 798 801 800 798	442 441 442 442 442	1727 1725 1730 1720 1720	1743 1741 1749 1743 1749	1765 1765 1760 1780 1780	43.64 45.77 43.69 45.57 43.62	2824 2824 2824 2824 2853	7040 8078 5240 4494 3582	0.0844 .0590 .0527 .0478 .0405	0.0633 .0544 .0472 .0408 .0304
40,000	0.611 .614 .612 .608	385 384 385 386	495 495 495 495	425 422 421 421	1087 1085 1085 1094	1755 1761 1755 1759	1770 1765 1770 1765	27.66 27.72 27.83 27.83	1840 1849 1849 1856	4113 5248 2548 1816	0.0814 .0524 .0430 .0376	0.0590 .0488 .0356 .0281
50,000	0.642 .643 .642 .653	235 235 235 235	310 310 310 313	425 424 425 424	665 665 668 673	1746 1765 1751 1754	1775 1775 1775 1775	17.21 17.19 17.24 17.29	1161 1176 1185 1171	2229 1820 1380 1075	0.0562 .0497 .0418 .0371	0.0518 .0428 .0321 .0255
Configuration C,												
15,000	0.811 .608 .810 .809 .610 .610 .610 .608	1186 1186 1186 1186 1186 1183 1174 1182 1184	1525 1522 1526 1525 1526 1520 1516 1519 1519	543 544 544 546 546 546 547 547 549	2890 2888 2898 2897 2895 2855 2846 2856 2872	1778 1760 1755 1755 1765 1755 1755 1755 1758	1770 1765 1765 1765 1765 1765 1760 1760 1755	72.65 72.71 72.85 72.81 72.51 72.51 72.09 72.19 71.62	4492 4425 4415 4388 4369 4369 4302 4311 4320	8200 7370 6520 5895 5361 5361 3940 5116 2645	0.0489 .0462 .0428 .0395 .0361 .0361 .0326 .0285 .0277	0.0436 .0390 .0344 .0301 .0256 .0210 .0186 .0143

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PERFORMANCE DATA

Exhaust-nozzle-inlet total pressure, F_g , lb sq ft abs	Exhaust-nozzle- total temper- ature, A_{10} , sq ft or	Exhaust-nozzle area, A_{10} , sq ft	Afterburner temperature ratio, T_{10}/T_5	Augmented jet thrust, F_j , lb	Augmented jet thrust ratio, F_j/F_j	Net thrust, F_n , lb	Augmented net thrust ratio, F_n/F_n	Net thrust specific fuel con- sumption, ($W_{f,e} + W_{f,ab}$) F_n	Engine combus- tion effici- ency, η_e	Afterburner combustion efficiency, η_{ab}	Maximum- after- burner shell tempera- ture, T_R	Afterburner pressure- loss ratio, F_g/F_g
Configuration A												
2870	3131	5.04	1.763	6248	1.297	4778	1.427	2.412	0.990	0.883	1990	0.1034
2684	3000	2.92	1.663	6106	1.262	4617	1.379	2.264	0.990	0.916	1910	0.1018
2879	2880	2.89	1.617	6013	1.235	4514	1.339	2.191	0.990	0.919	1871	0.1013
2588	2735	2.82	1.543	5787	1.208	4314	1.297	2.109	0.990	0.907	1800	0.0868
2677	2574	2.72	1.453	5591	1.167	4104	1.242	2.058	0.990	0.866	1750	0.0959
1427	3582	3.22	1.865	3552	1.341	3110	1.409	2.570	0.990	0.768	2022	0.1159
1428	3274	3.10	1.816	3500	1.317	3041	1.384	2.328	0.990	0.847	1851	0.1120
1435	3136	2.98	1.739	3417	1.264	2955	1.344	2.158	0.990	0.912	1805	0.1093
1419	2982	2.92	1.663	3249	1.248	2826	1.296	1.992	0.990	0.981	1729	0.1076
1444	2670	2.79	1.485	3125	1.181	2663	1.219	1.908	0.990	0.827	1882	0.1008
1445	2538	2.69	1.407	3037	1.144	2578	1.174	1.805	0.990	0.874	1549	0.1004
1610	3237	3.07	1.814	4130	1.326	3341	1.436	2.292	0.990	0.874	1934	0.1090
1606	3182	3.01	1.777	4057	1.307	3278	1.410	2.216	0.990	0.889	1850	0.1093
1609	3030	2.99	1.687	3948	1.276	3169	1.389	2.158	0.990	0.885	1782	0.1057
1635	2689	2.92	1.650	3918	1.248	3132	1.351	2.055	0.990	0.896	1800	0.1051
1613	2761	2.82	1.548	3772	1.213	2974	1.287	1.964	0.990	0.897	1750	0.1014
1622	2544	2.69	1.430	3587	1.183	2804	1.219	1.878	0.990	0.847	1663	0.0984
1894	3245	3.10	1.857	5187	1.345	5896	1.519	2.302	0.990	0.852	2101	0.1083
1856	3089	3.01	1.744	4835	1.305	5690	1.454	2.214	0.990	0.868	1882	0.1081
1870	2923	2.95	1.645	4601	1.280	5357	1.391	2.088	0.990	0.884	1770	0.1018
1875	2701	2.82	1.527	4601	1.242	5354	1.318	1.987	0.990	0.862	1714	0.0981
1872	2420	2.69	1.402	4370	1.158	5134	1.292	1.890	0.990	0.831	1582	0.0982
1900	2368	2.58	1.339	4311	1.150	5050	1.194	1.808	0.990	0.822	1440	0.0912
2277	2758	2.82	1.653	6067	1.273	4254	1.444	2.003	0.990	0.946	1926	0.0978
2275	2685	2.79	1.633	6050	1.255	4179	1.417	1.991	0.990	0.921	1888	0.0991
2315	2657	2.71	1.570	6018	1.239	4155	1.387	1.941	0.990	0.938	1897	0.0939
2322	2626	2.68	1.521	5889	1.215	4016	1.351	1.905	0.990	0.920	1817	0.0951
2307	2629	2.55	1.472	5791	1.195	3927	1.318	1.856	0.990	0.826	1736	0.0939
2306	2460	2.56	1.377	5569	1.153	3709	1.250	1.826	0.990	0.854	1720	0.0914
1001	3472	3.35	1.886	2738	1.553	2248	1.480	2.860	0.987	0.699	1995	0.1288
1014	3306	3.22	1.808	2669	1.327	2180	1.431	2.622	0.987	0.72h	1910	0.1215
1019	3163	3.10	1.752	2644	1.302	2148	1.399	2.434	0.987	0.760	1870	0.1170
1017	3101	3.04	1.694	2545	1.275	2068	1.361	2.263	0.987	0.820	1793	0.1110
1016	3018	2.95	1.648	2510	1.255	2021	1.333	2.106	0.987	0.887	1745	0.1148
1015	2861	2.85	1.552	2408	1.211	1934	1.277	2.013	0.987	0.887	1678	0.1089
1021	2600	2.72	1.415	2298	1.154	1824	1.202	1.910	0.987	0.800	1598	0.1067
612	3496	3.35	1.902	1697	1.364	1564	1.497	2.349	0.967	0.684	1817	0.1377
612	3411	3.31	1.872	1680	1.347	1552	1.471	2.354	0.967	0.727	1820	0.1381
615	3585	3.22	1.857	1684	1.338	1548	1.480	2.585	0.966	0.760	1781	0.1361
632	3144	3.10	1.729	1644	1.287	1316	1.387	2.387	0.966	0.776	1717	0.1270
631	3104	3.04	1.700	1607	1.271	1289	1.363	2.261	0.966	0.829	1668	0.1244
vanes and vortex generators added												
1593	3360	3.26	1.928	4275	1.411	3456	1.563	2.854	0.990	0.679	1769	0.0776
1601	3270	3.18	1.878	4203	1.385	3386	1.527	2.629	0.990	0.726	1719	0.0719
1611	3220	3.12	1.841	4152	1.366	3330	1.503	2.427	0.990	0.795	1718	0.0588
1606	3152	3.08	1.808	4073	1.348	3269	1.477	2.245	0.990	0.866	1702	0.0663
1616	2880	2.95	1.647	3667	1.279	3056	1.381	2.027	0.990	0.904	1619	0.0601
1002	3210	3.25	1.829	2656	1.368	2146	1.500	2.774	0.987	0.654	1681	0.0782
1005	3200	3.17	1.817	2638	1.354	2125	1.481	2.399	0.987	0.796	1680	0.0737
1013	2968	3.03	1.693	2530	1.297	2017	1.403	2.081	0.987	0.694	1659	0.0664
1026	2669	2.87	1.517	2395	1.223	1885	1.301	1.948	0.986	0.848	1629	0.0622
607	3108	3.24	1.780	1611	1.356	1278	1.464	2.553	0.964	0.681	1600	0.0868
611	2988	3.12	1.692	1572	1.297	1239	1.410	2.416	0.966	0.730	1600	0.0804
615	2613	2.97	1.492	1486	1.211	1152	1.290	2.225	0.963	0.66	1574	0.0754
627	2571	2.82	1.466	1460	1.197	1120	1.273	2.005	0.966	0.776	1555	0.0692
straightening vanes and liner												
2691	3228	3.12	1.816	6454	1.350	4936	1.512	2.571	0.990	0.825	1561	0.0689
2695	3106	3.06	1.765	6324	1.327	4810	1.480	2.452	0.990	0.843	1555	0.0668
2711	3008	2.97	1.716	6228	1.306	4705	1.449	2.324	0.990	0.873	1550	0.0645
2717	2867	2.91	1.654	6063	1.271	4541	1.399	2.220	0.990	0.876	1540	0.0621
2674	2735	2.82	1.558	5851	1.256	4513	1.348	2.129	0.990	0.898	1519	0.0634
2677	2570	2.70	1.474	5626	1.200	4102	1.295	2.009	0.990	0.902	1516	0.0594
2699	2322	2.58	1.351	5358	1.158	3826	1.204	1.941	0.990	0.790	1494	0.0540
2722	2153	2.49	1.225	5107	1.091	3609	1.133	1.830	0.990	0.653	1490	0.0422

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TABLE II. - Concluded.

Altitude, ft	Flight Mach number, M_0	Free-stream static pressure, P_0 , lb/sq ft abs	Engine-inlet total pressure, P_1 , lb/sq ft abs	Engine-inlet total temperature, T_1 , °R	Turbine-outlet total pressure, P_2 , lb/sq ft abs	Turbine-outlet total temperature, T_2 , °R	Manufacturer's turbine-outlet control temperature, $T_{5,m}$, °R	Engine-inlet air flow, $W_{a,1}$, lb/sec	Engine fuel flow, $W_{f,a}$, lb/hr	Afterburner fuel flow, $W_{f,ab}$, lb/hr	Total fuel-air ratio, f	Afterburner fuel-air ratio, f_{ab}
Configuration C,												
30,000	0.604 .606 .604 .609 .611 .616	.625 .621 .624 .624 .620 .622	799 795 798 802 798 802	444 443 442 441 439 445	1725 1711 1721 1721 1724 1703	1751 1750 1749 1742 1745 1739	1765 1765 1765 1765 1765 1765	43.82 43.49 43.69 43.81 43.73 43.74	2833 2833 2833 2833 2850 2807	7775 6427 5137 3957 2879 1797	0.0644 .0607 .0520 .0442 .0373 .0300	0.0689 .0582 .0483 .0355 .0280 .0163
40,000	0.600 .598 .597 .608 .611 .612	368 398 390 387 384 387	494 494 497 496 497 498	422 422 425 429 424 421	1093 1094 1091 1084 1093 1104	1768 1768 1766 1765 1770 1765	1785 1785 1770 1765 1765 1765	27.78 27.77 27.61 27.50 27.71 27.97	1865 1865 1849 1852 1857 1872	4451 3784 3005 2513 1607 1088	0.0644 .0580 .0453 .0358 .0233 .0165	0.0632 .0545 .0433 .0336 .0233 .0165
50,000	0.605 .598 .611 .606 .629	239 238 236 241 234	306 308 304 308 305	425 424 427 423 423	672 659 653 668 669	1801 1792 1758 1806 1806	1765 1765 1765 1765 1760	17.05 17.07 16.74 17.08 17.07	1197 1192 1142 1207 1202	2845 2227 1790 1297 669	0.0644 .0572 .0500 .0419 .0313	0.0631 .0531 .0433 .0314 .0167
Configuration D, modified fuel distribution												
15,000	0.614 .613 .614	1165 1188 1187	1527 1532 1531	539 533 537	2897 2847 2920	1737 1738 1741	1780 1780 1780	73.39 74.14 75.67	4387 4384 4434	8021 5800 4512	0.0482 .0395 .0350	0.0418 .0301 .0241
30,000	0.598 .594 .404 .412	634 632 704 625 626	707 704 426 700 425	427 426 1536 1528 1554	1546 1536 1536 1748 1740	1749 1742 1760 1760 1755	1770 1760 1760 1760 1755	39.35 39.24 39.05 39.38	2580 2582 2553 2580	5614 4193 5035 1980	0.0584 .0481 .0409 .0350	0.0553 .0442 .0308 .0200
30,000	0.610 .608 .61C .61C .602 .603	624 628 624 625 630	802 805 802 798 805	438 436 444 445 445	1740 1734 1709 1712 1723	1748 1738 1755 1752 1746	1785 1780 1755 1755 1755	44.18 44.39 43.65 43.50 43.80	2876 2876 2818 2853 2833	6217 5261 4213 3025 2028	0.0583 .0422 .0459 .0384 .0207	0.0583 .0486 .0379 .0275 .0207
30,000	0.609 .614 .604 .800 .818	625 986 926 962 820	961 986 959 962 962	463 460 472 456 455	2027 2031 1995 2039 2042	1754 1759 1749 1742 1748	1770 1760 1765 1760 1760	51.21 51.75 50.48 51.68 51.80	3287 3287 3208 3237 3234	7706 5506 4795 3765 3007	0.0512 .0507 .0452 .0390 .0348	0.0589 .0446 .0372 .0286 .0229
40,000	0.600 .596 .594 .600 .592	391 393 394 394 393	498 499 499 499 498	415 416 423 423 422	1104 1103 1095 1097 1098	1755 1749 1749 1755 1761	1785 1785 1785 1785 1770	28.25 28.30 28.07 28.04 28.00	1888 1880 1856 1856 1865	4094 3514 2844 2128 1502	0.0504 .0543 .0477 .0406 .0343	0.0577 .0493 .0402 .0305 .0215
50,000	0.658 .636 .619 .653 .638 .637	255 237 239 235 234 235	315 311 310 312 308 309	420 419 418 417 417 418	679 678 678 672 672 668	1752 1770 1775 1747 1768 1769	1775 1772 1765 1770 1765 1775	17.55 17.54 17.25 17.46 17.32 17.33	1190 1190 1190 1182 1180 1190	2663 2505 2194 1874 1513 1229	0.0627 .0609 .0580 .0499 .0448 .0398	0.0608 .0583 .0516 .0433 .0356 .0290
Configuration E, modified fuel												
40,000	0.589 .610 .601 .667 .573 .584	396 389 394 403 401 397	500 500 503 501 501 500	421 423 423 423 422 423	1092 1085 1087 1092 1091 1080	1748 1742 1742 1742 1741 1742	1750 1745 1745 1745 1745 1745	28.07 28.18 28.15 28.12 28.24 28.15	1825 1817 1825 1825 1825 1826	3948 3580 3584 3188 2778 2285	0.0586 .0557 .0525 .0508 .0465 .0415	0.0553 .0514 .0470 .0466 .0387 .0320
50,000	0.632 .623 .626 .624	237 243 236 236	310 316 307 307	432 431 433 432	659 666 680 661	1793 1760 1773 1764	1770 1760 1770 1765	17.08 17.37 16.90 16.98	1171 1151 1142 1157	2717 2275 2030 1488	0.0649 .0586 .0535 .0441	0.0638 .0526 .0482 .0352
Configuration F, original with												
30,000	0.592 .590 .591 .592 .590 .590	634 631 632 628 633 636	804 441 798 445 801 438	443 1759 1774 1775 1774 1778	1765 1755 1760 1755 1755 1755	1760 1755 1760 1755 1755 1755	43.67 43.44 43.67 43.23 43.74 43.92	2876 2876 2911 2911 2911 2928	6495 5655 4955 4311 3228 2243	0.0611 .0560 .0513 .0461 .0400 .0335	0.0587 .0516 .0451 .0396 .0294 .0204	
40,000	0.580 .593 .584 .593 .586 .580	395 394 394 391 391 395	500 500 496 496 495 500	417 415 414 426 429 414	1149 1149 1140 1139 1130 1151	1812 1810 1797 1801 1816 1803	1780 1780 1770 1780 1775 1775	28.07 28.06 28.01 27.57 27.37 28.10	1980 1980 1936 1896 1903 1968	4073 5475 2934 2408 1901 1465	0.0613 .0552 .0496 .0455 .0396 .0346	0.0587 .0502 .0423 .0355 .0282 .0211

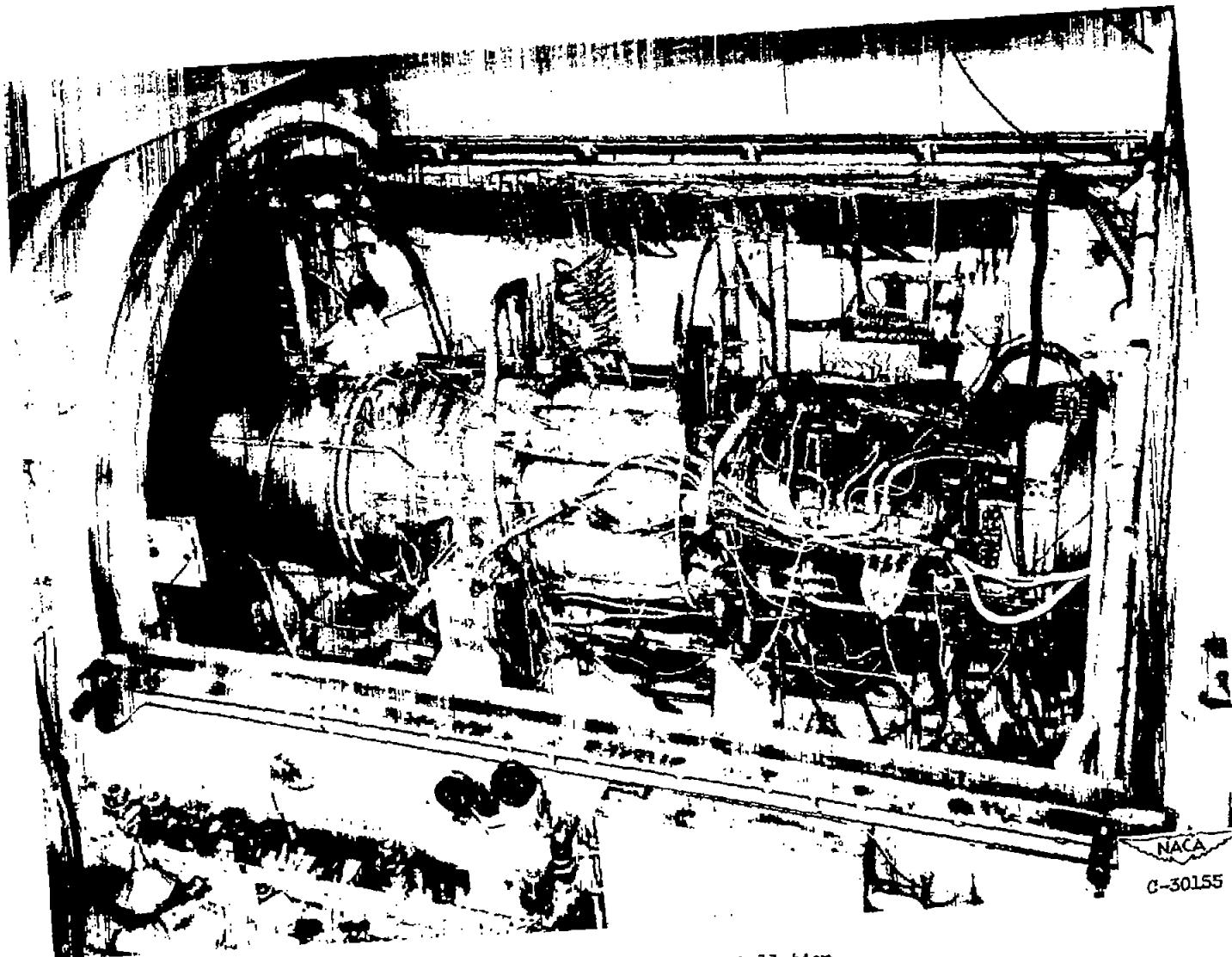
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ALTITUDE PERFORMANCE DATA

Exhaust-nozzle-inlet total pressure, P_g , lb sq ft abs	Exhaust-nozzle-total temperature, T_{10} , °R	Exhaust-nozzle area, A_{10} , sq ft	Afterburner temperature ratio, T_{10}/T_5	Augmented jet thrust, F_j , lb	Augmented jet thrust ratio, $F_j/F_{j,ab}$	Net thrust, F_n , lb	Augmented net thrust ratio, $F_n/F_{n,ab}$	Net thrust specific fuel consumption, $(W_{f,g}W_{f,ab})/F_n$	Engine combustion efficiency, η_e	Afterburner combustion efficiency, η_{ab}	Maximum-afterburner shell temperature, °R	Afterburner pressure-loss ratio, P_g/P_5
straightening vanes and liner												
1579	3271	5.31	1.868	4209	1.390	3393	1.535	3.126	0.990	0.589	1584	0.0536
1571	3508	5.29	1.890	4185	1.388	3570	1.531	2.748	0.930	.704	1599	.0618
1584	3199	5.19	1.829	4103	1.354	3288	1.484	2.424	0.930	.758	1588	.0796
1597	3048	5.07	1.750	3398	1.318	3173	1.436	2.140	0.930	.904	1559	.0721
1615	2783	2.89	1.594	3609	1.252	2987	1.345	1.918	0.990	.955	1540	.0644
1610	2529	2.58	1.533	3446	1.143	2612	1.198	1.763	0.990	.844	1489	.0546
997	3170	3.30	1.793	2854	1.355	2150	1.475	2.828	0.987	0.600	1590	0.0582
1001	3186	3.24	1.802	2637	1.349	2135	1.469	2.646	0.987	.689	1592	.0650
1000	3107	3.19	1.759	2564	1.322	2084	1.434	2.352	0.987	.753	1610	.0636
1000	2976	5.03	1.684	2484	1.286	1975	1.389	2.099	0.986	.856	1600	.0779
1019	2652	2.82	1.498	2372	1.210	1853	1.286	1.869	0.987	.920	1491	.0677
1036	2236	2.62	1.550	2193	1.108	1677	1.146	1.753	0.986	.727	1460	.0598
608	3026	5.31	1.680	1573	1.301	1260	1.408	3.049	0.987	0.555	1599	0.0952
596	3022	5.26	1.686	1554	1.294	1245	1.396	2.746	0.986	.617	1600	.0966
596	2925	5.15	1.664	1491	1.260	1181	1.381	2.483	0.983	.687	1610	.0915
613	2686	2.96	1.487	1452	1.202	1139	1.273	2.198	0.987	.707	1499	.0816
620	2129	2.65	1.179	1297	1.062	975	1.085	1.923	0.987	.486	1481	.0735
with straightening vanes and liner												
2662	3408	5.19	1.962	6662	1.392	5127	1.577	2.420	0.990	0.974	1612	0.0811
2750	2957	2.95	1.701	6301	1.284	4761	1.451	2.156	0.990	.954	1582	.0669
2735	2728	2.82	1.567	5986	1.241	4446	1.353	2.035	0.990	.948	1569	.0634
1409	3557	5.50	2.034	3669	1.424	3185	1.522	2.572	0.990	0.641	1818	0.0886
1414	3238	5.22	1.859	3470	1.355	2991	1.437	2.259	0.990	.853	1570	.0794
1421	2916	5.01	1.668	3273	1.279	2785	1.345	2.010	0.990	.927	1535	.0700
1464	2362	2.69	1.339	2994	1.153	2494	1.189	1.828	0.990	.741	1489	.0579
1591	3548	5.50	2.032	4415	1.434	3587	1.594	2.563	0.990	0.836	1739	0.0856
1594	3555	5.51	1.951	4274	1.391	3447	1.535	2.581	0.990	.882	1587	.0807
1585	3142	5.15	1.801	4036	1.340	3212	1.467	2.188	0.990	.914	1580	.0726
1602	2828	2.92	1.614	3799	1.261	2987	1.357	1.961	0.990	.943	1619	.0643
1625	2456	2.72	1.407	3555	1.174	2734	1.239	1.778	0.990	.908	1490	.0569
1880	3566	5.50	2.033	5474	1.447	4198	1.675	2.619	0.990	0.807	1772	0.0824
1875	3346	5.22	1.924	5312	1.355	4019	1.599	2.290	0.990	.904	1590	.0788
1814	5126	5.10	1.768	4853	1.343	3689	1.522	2.169	0.990	.914	1549	.0707
1910	2870	2.92	1.648	4660	1.279	3598	1.418	1.984	0.990	.947	1529	.0633
1921	2614	2.75	1.495	4669	1.216	3576	1.325	1.875	0.990	.901	1500	.0583
1003	3407	5.50	1.941	2773	1.400	2266	1.537	2.640	0.987	0.760	1736	0.0915
1007	3306	5.29	1.830	2722	1.375	2216	1.503	2.434	0.987	.817	1590	.0870
1005	3080	5.18	1.761	2583	1.321	2078	1.435	2.282	0.987	.835	1580	.0822
1015	2835	2.98	1.615	2461	1.258	1952	1.348	2.041	0.987	.878	1528	.0748
1027	2393	2.75	1.359	2255	1.151	1754	1.202	1.920	0.987	.709	1483	.0647
611	3364	5.46	1.932	1729	1.394	1383	1.547	2.786	0.967	0.714	1609	0.1002
612	3339	5.37	1.886	1890	1.376	1359	1.518	2.719	0.967	.717	1600	.0978
614	3229	5.28	1.816	1841	1.346	1320	1.470	2.584	0.967	.745	1595	.0930
615	3132	5.16	1.793	1638	1.335	1298	1.460	2.554	0.965	.814	1571	.0884
618	2814	2.98	1.592	1535	1.260	1203	1.357	2.243	0.967	.758	1485	.0811
618	2694	2.89	1.525	1493	1.220	1162	1.301	2.082	0.967	.788	1513	.0745
distribution with uniformific spray bar												
992	3465	5.50	1.982	2745	1.411	2250	1.563	2.566	0.985	0.815	---	0.0916
983	3508	5.22	1.859	2690	1.376	2173	1.511	2.530	0.985	.791	---	.0940
988	3257	5.16	1.870	2657	1.362	2146	1.480	2.418	0.985	.828	---	.0911
994	3218	5.10	1.847	2614	1.352	2130	1.468	2.353	0.985	.843	---	.0888
998	3092	5.01	1.776	2568	1.322	2078	1.450	2.215	0.985	.875	---	.0853
994	2907	2.89	1.669	2480	1.277	1982	1.373	2.074	0.985	.801	---	.0796
598	3548	5.50	1.867	1557	1.375	1329	1.515	2.928	0.963	0.666	---	0.0956
606	3228	5.17	1.854	1622	1.355	1294	1.489	2.646	0.983	.733	---	.0901
601	3146	5.06	1.774	1578	1.329	1255	1.453	2.327	0.982	.745	---	.0894
607	2912	2.89	1.632	1514	1.266	1191	1.364	2.204	0.961	.815	---	.0817
fuel distribution away from shell												
1584	3562	5.28	1.807	4188	1.355	3386	1.502	2.785	0.990	0.720	1812	0.1159
1561	3457	5.08	1.808	4186	1.344	3374	1.494	2.528	0.990	.816	1849	.1126
1576	3231	5.16	1.815	4080	1.301	3286	1.442	2.389	0.990	.829	1910	.1096
1573	3206	5.04	1.803	3976	1.285	3182	1.412	2.256	0.990	.913	1790	.1047
1583	2634	2.92	1.600	3798	1.264	3004	1.316	2.044	0.990	.886	1722	.1020
1608	2522	2.72	1.418	3581	1.160	2783	1.212	1.858	0.990	.878	1600	.0961
1008	3523	5.25	1.834	2719	1.359	2221	1.450	2.716	0.987	0.701	1858	0.1227
1014	3280	5.19	1.812	3227	1.327	2193	1.433	2.478	0.987	.781	1804	.1175
1002	3207	5.17	1.785	2651	1.306	2141	1.405	2.275	0.987	.863	1832	.1211
1012	2970	2.98	1.649	2491	1.285	1995	1.340	2.157	0.987	.842	1716	.1099
1010	2779	2.89	1.530	2383	1.205	1894	1.273	2.008	0.987	.856	1661	.1082
1031	2418	2.75	1.341	2294	1.123	1798	1.163	1.909	0.987	.716	1610	.1043

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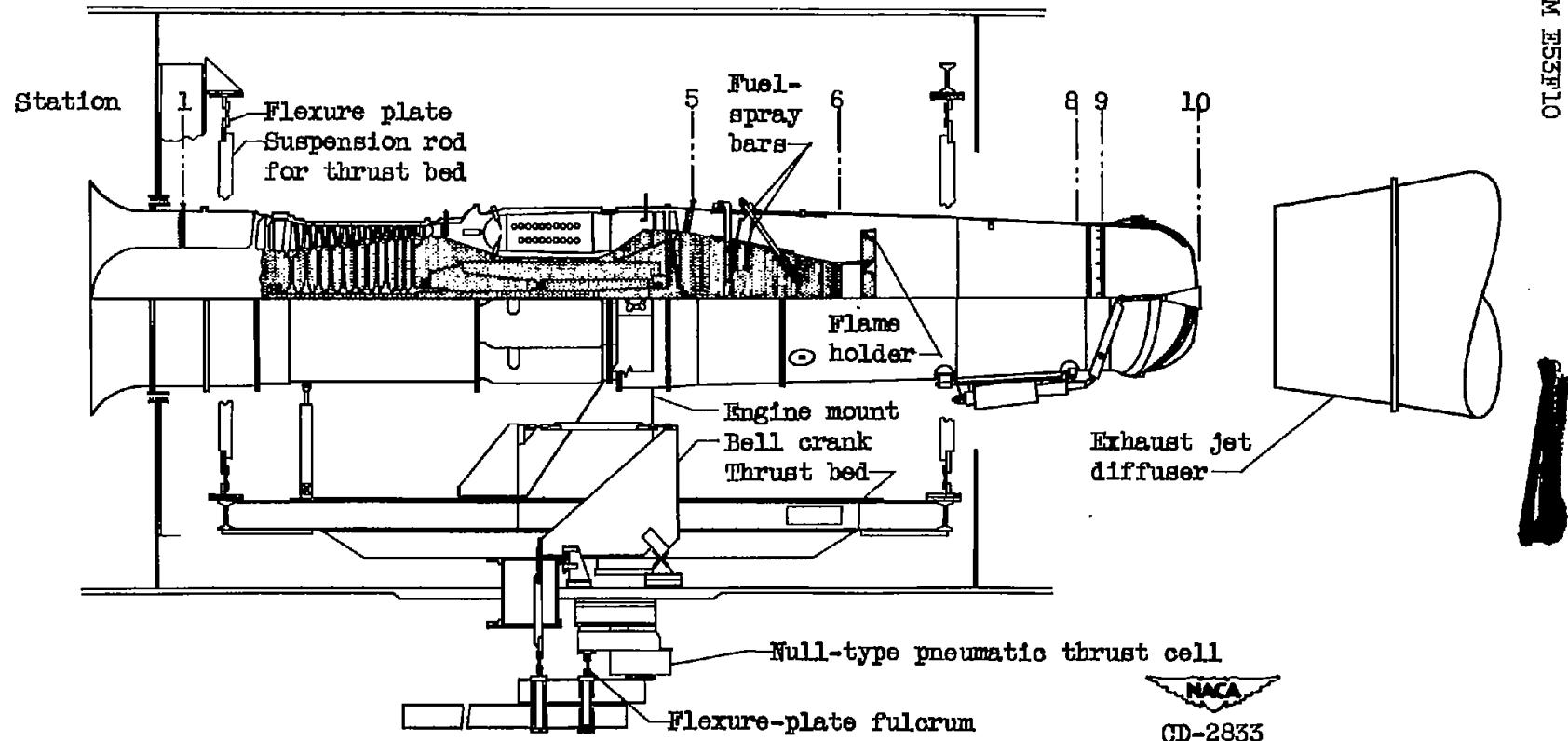


(a) Photograph of installation.

Figure 1. - Turbojet engine equipped with afterburner and installed in altitude chamber.

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(b) Schematic diagram of engine installation showing thrust-measuring system and instrumentation stations.

Figure 1. - Concluded. Turbojet engine equipped with afterburner and installed in altitude chamber.

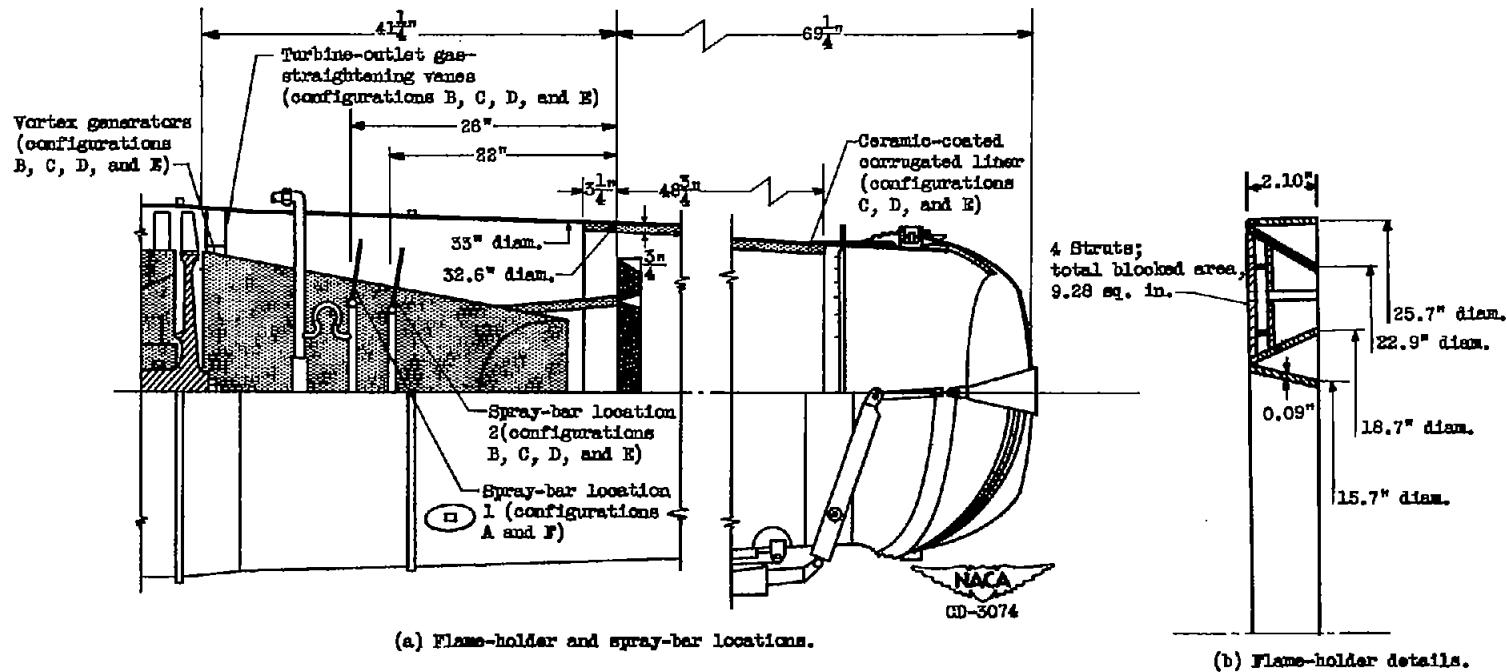
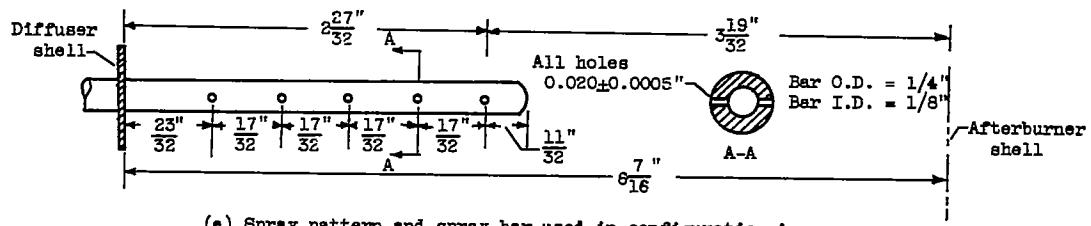
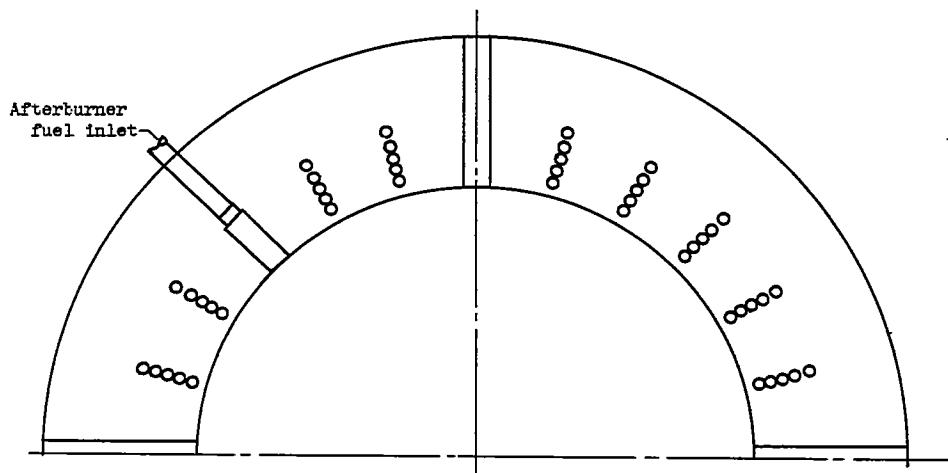
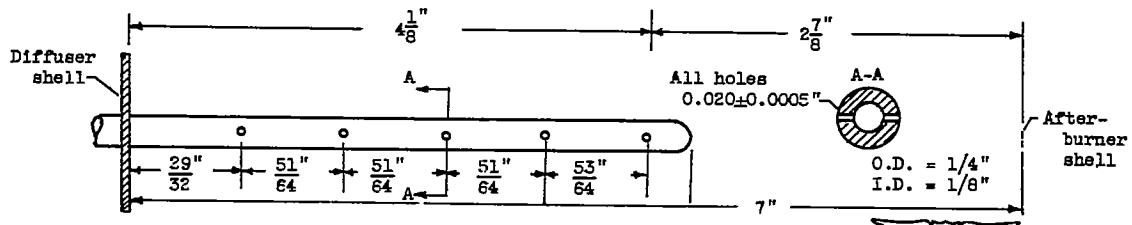
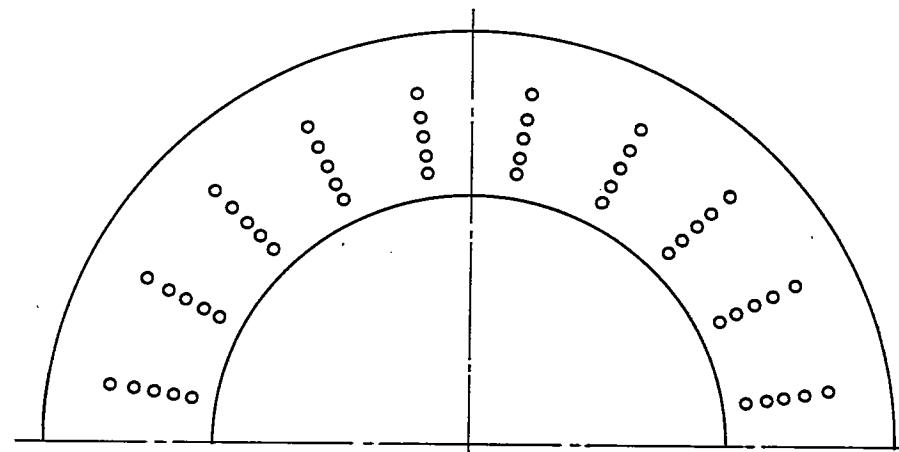


Figure 2. - Diagram of afterburner showing location of spray bars and flame holder.

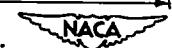


(a) Spray pattern and spray bar used in configuration A.



(b) Spray pattern and spray bar used in configurations B and C.

Figure 3. - Fuel-distribution patterns and spray-bar designs.



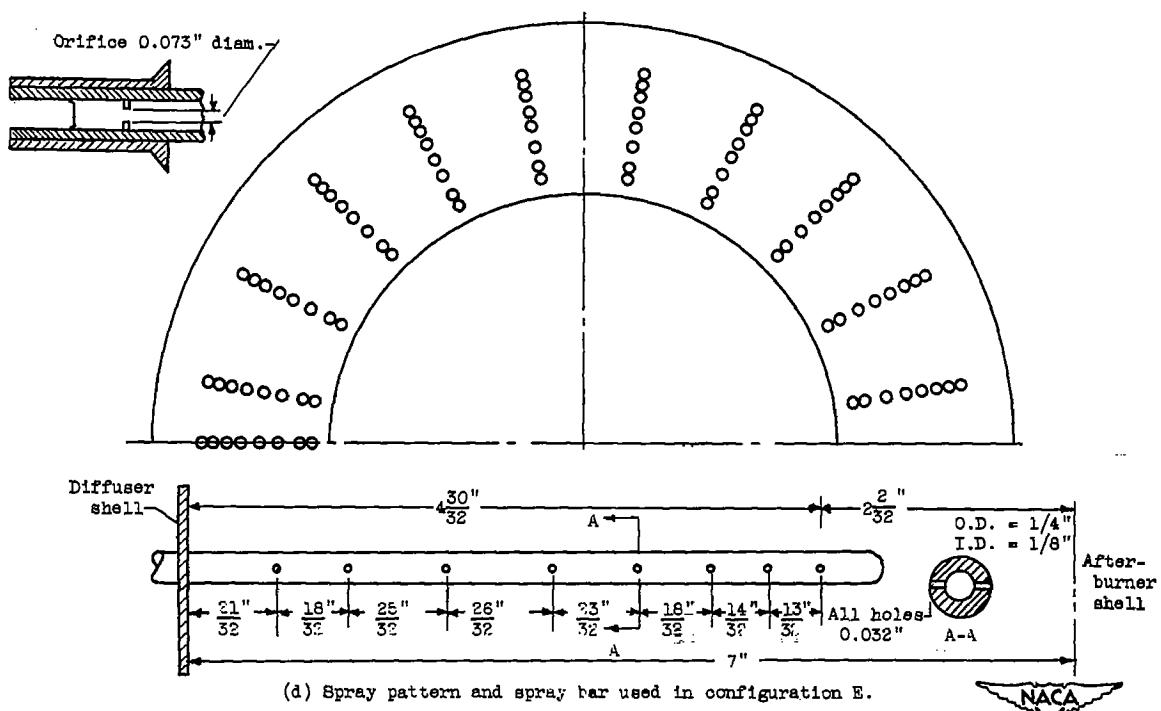
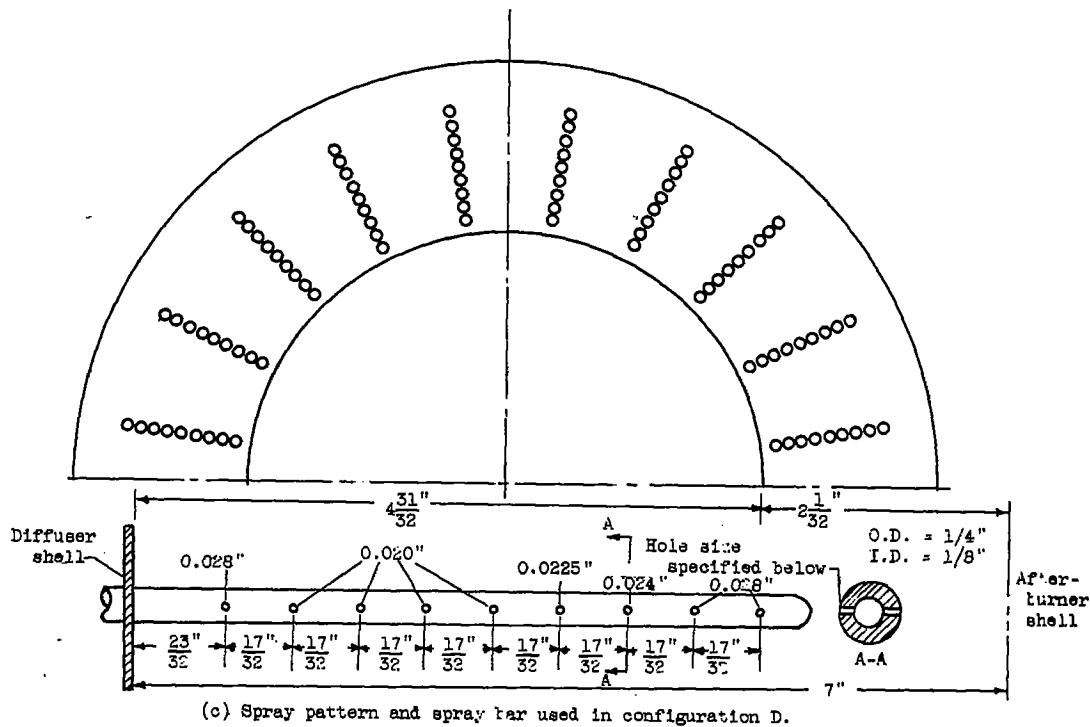
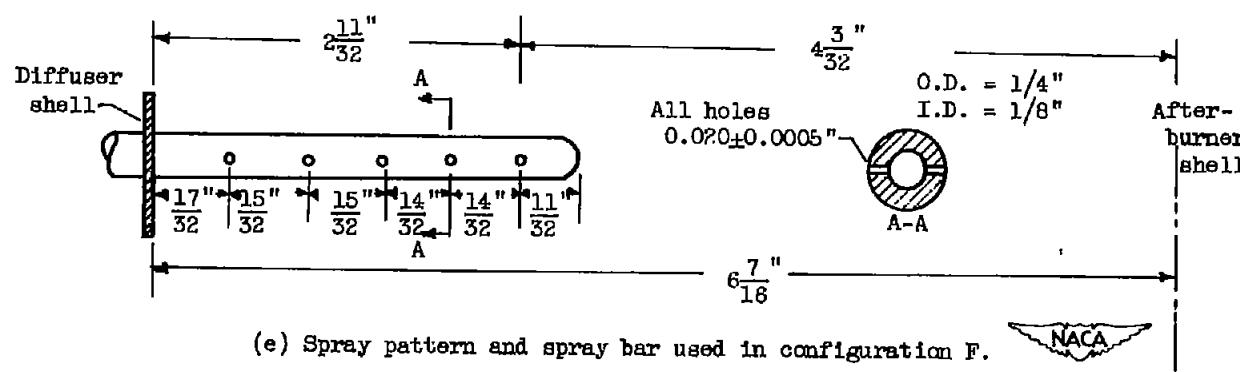
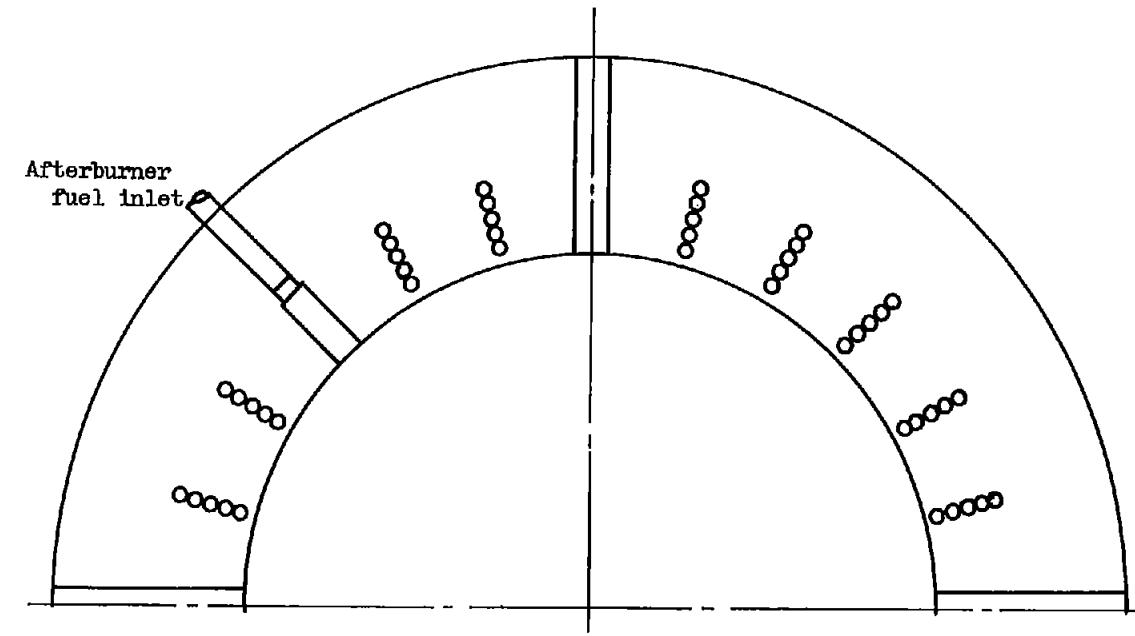


Figure 3. - Continued. Fuel-distribution patterns and spray-bar designs.





(e) Spray pattern and spray bar used in configuration F.

Figure 3. - Concluded. Fuel-distribution patterns and spray-bar designs.

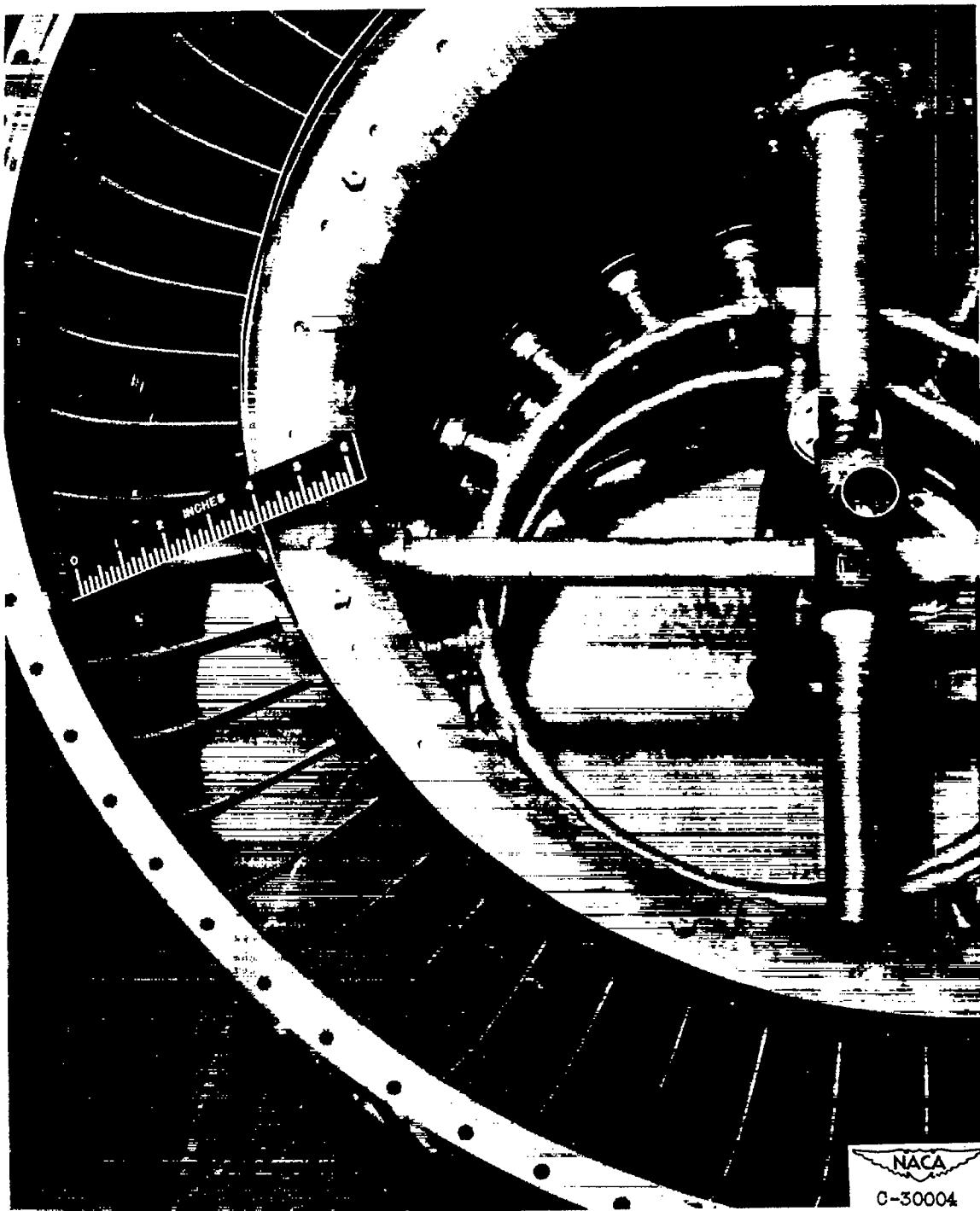


Figure 4. - Turbine-outlet gas-straightening vanes, vortex generators, and internal manifolds for configurations B, C, D, and E, as viewed in downstream direction.

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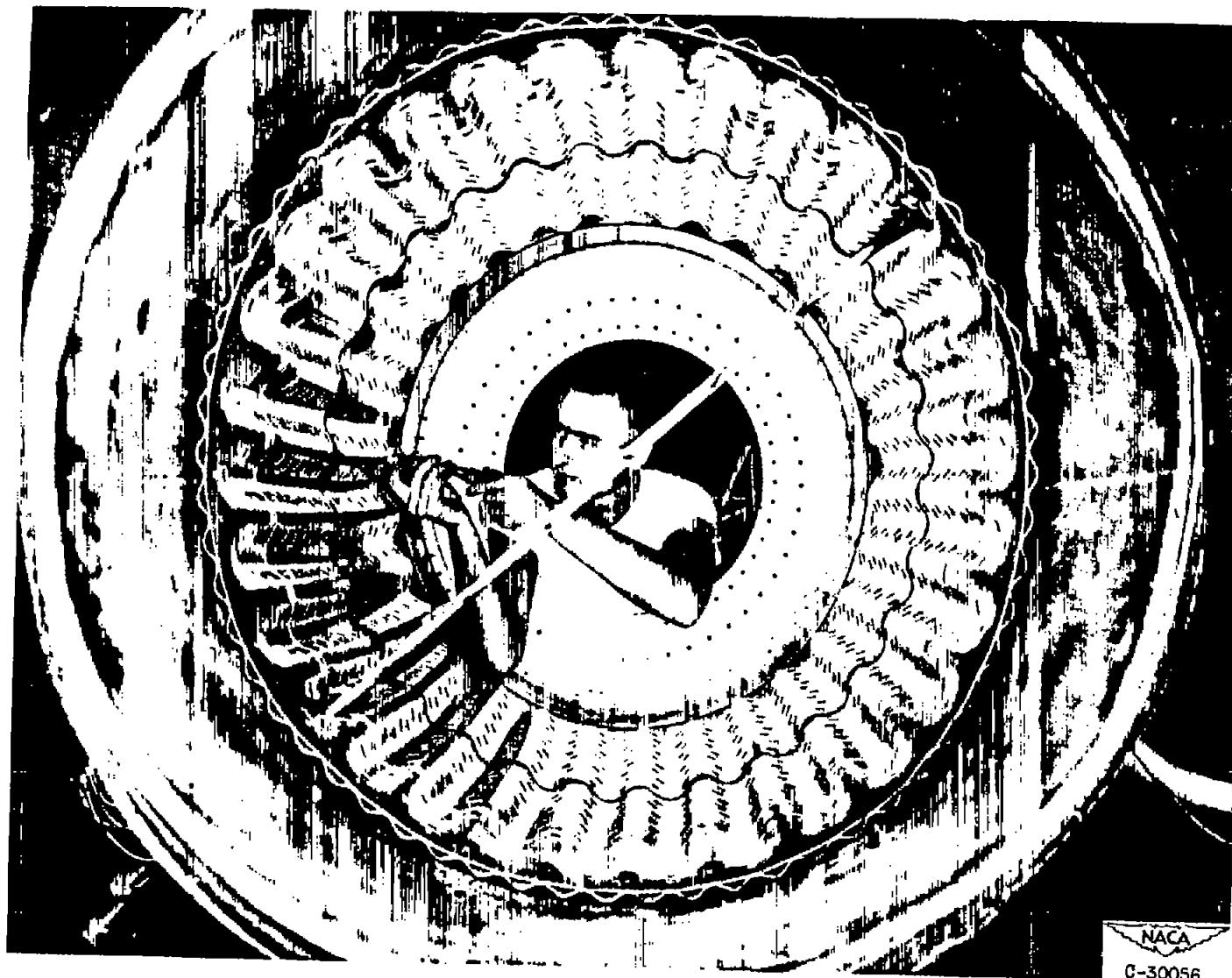
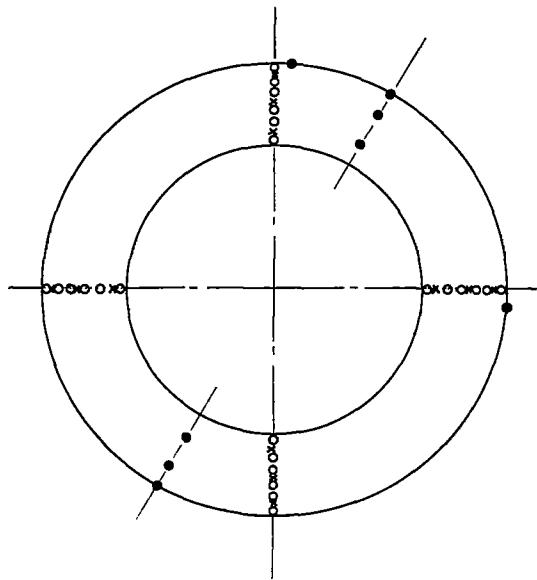
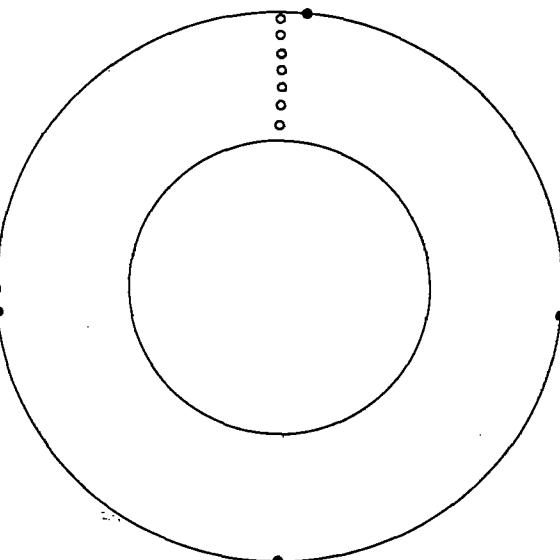


Figure 5. - Ceramic-coated corrugated liner installed in afterburner for configurations C, D, and E, as viewed in upstream direction.

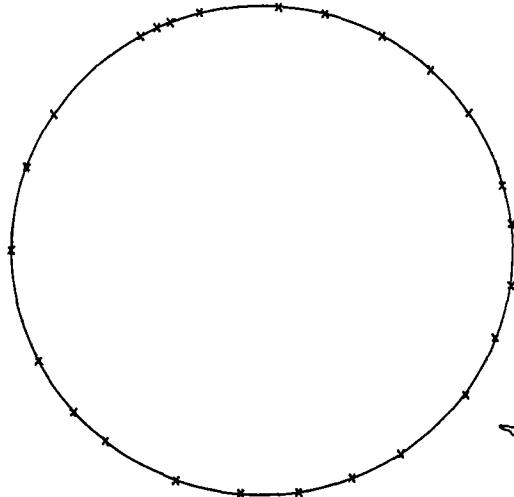
● Static-pressure tube (wall or rake)
 ○ Total-pressure tube
 ✕ Thermocouple



(a) Engine inlet, station 1, 21 inches upstream of leading edge of compressor-inlet guide vanes.



(b) Diffuser outlet, station 6, $37\frac{13}{16}$ inches downstream of turbine-outlet flange.



(c) Afterburner outer shell, station 8, $79\frac{5}{8}$ inches downstream of turbine-outlet flange.



(d) Nozzle inlet, station 9, $80\frac{3}{4}$ inches downstream of turbine-outlet flange.

Figure 6. - Instrumentation.

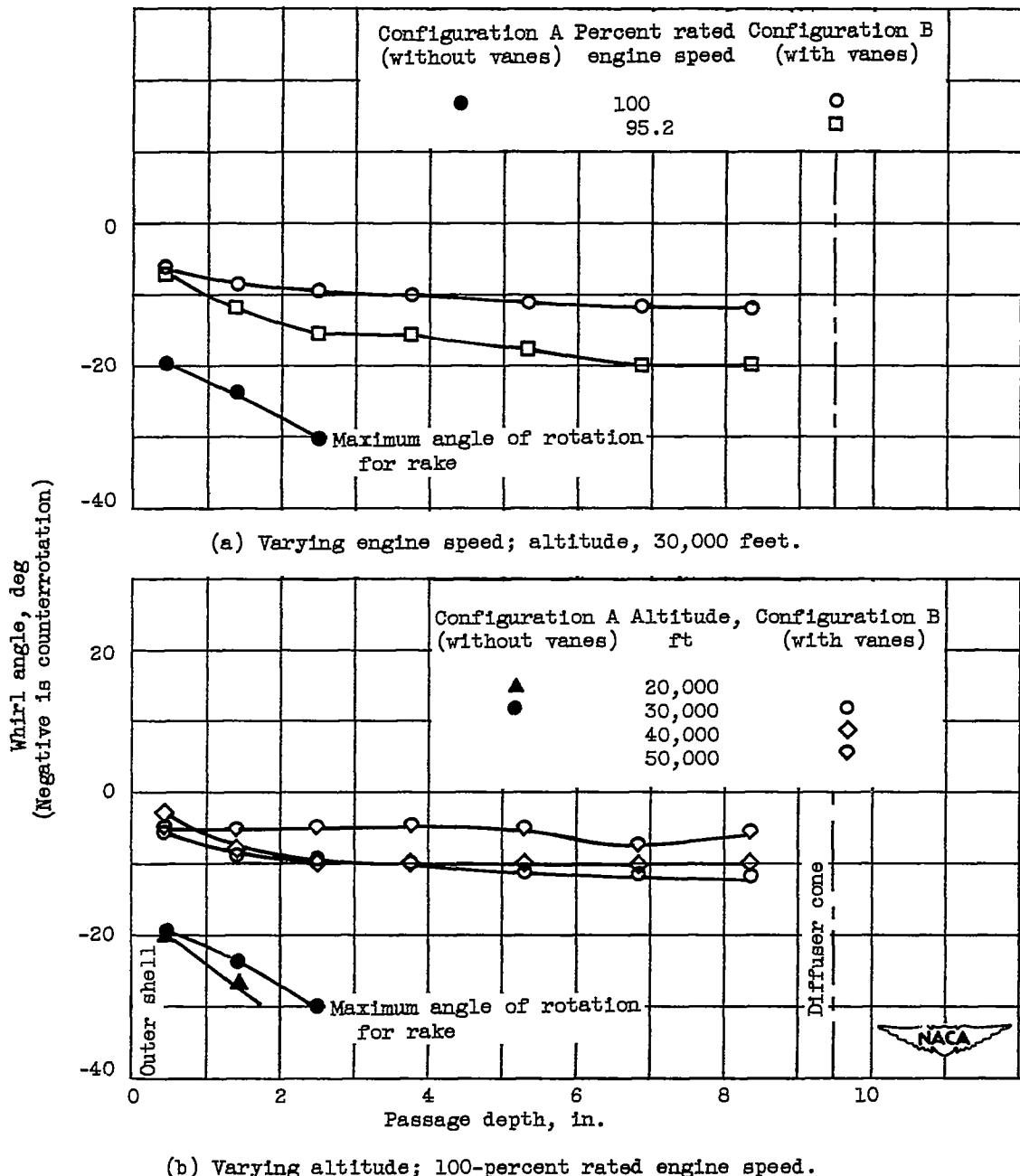


Figure 7. - Effect of engine speed and altitude on turbine-outlet gas whirl at flight Mach number of 0.6.

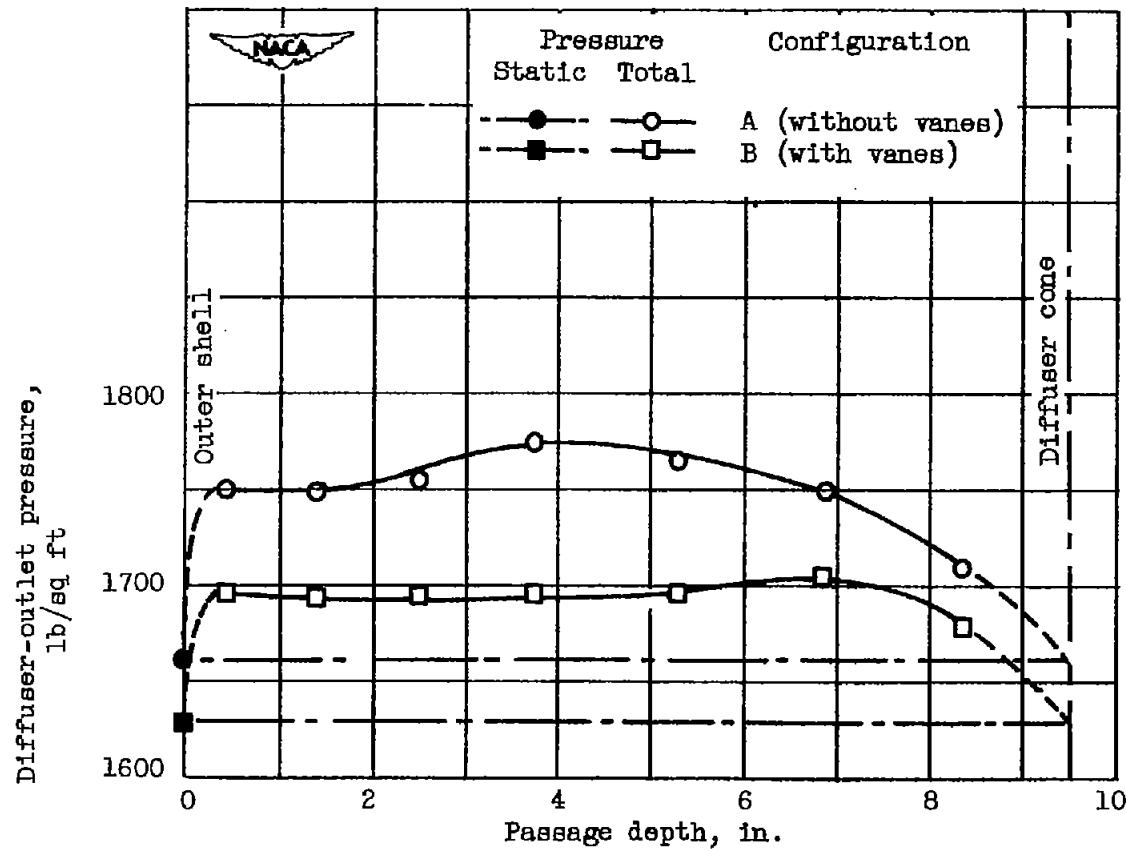


Figure 8. - Effect of turbine-outlet straightening vanes and vortex generators on diffuser-outlet total-pressure profile. Altitude, 30,000 feet; flight Mach number, 0.6.

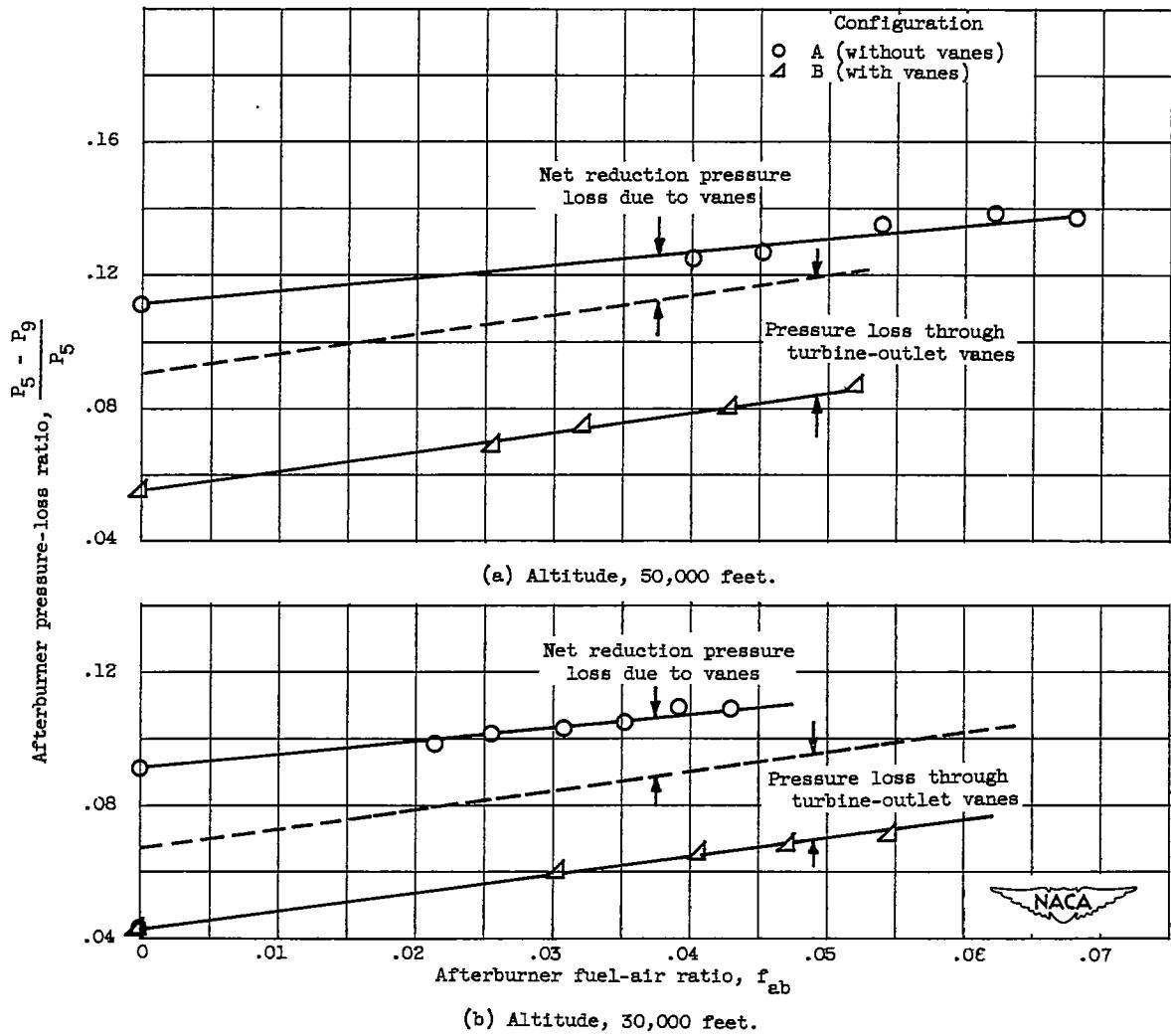
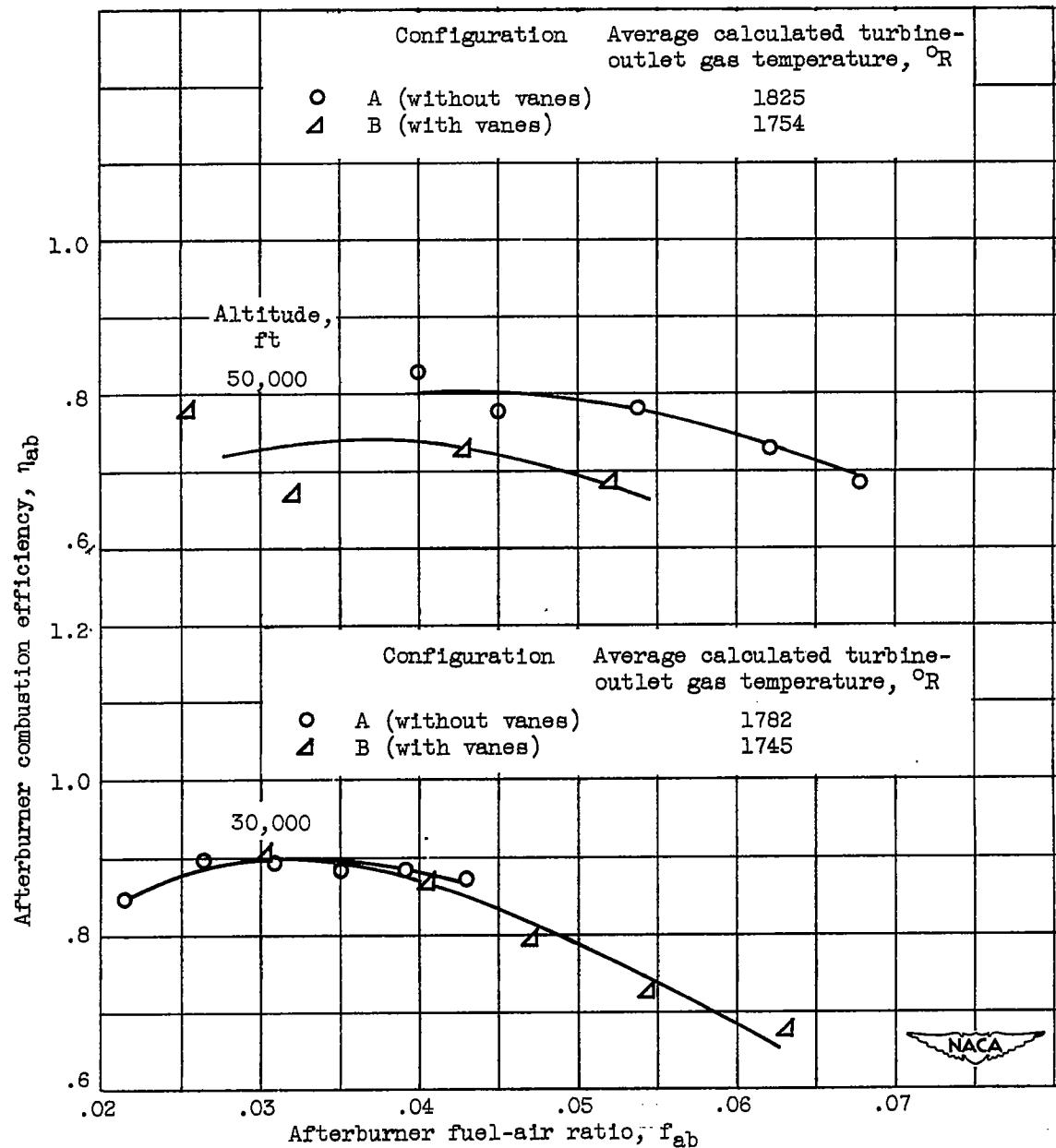
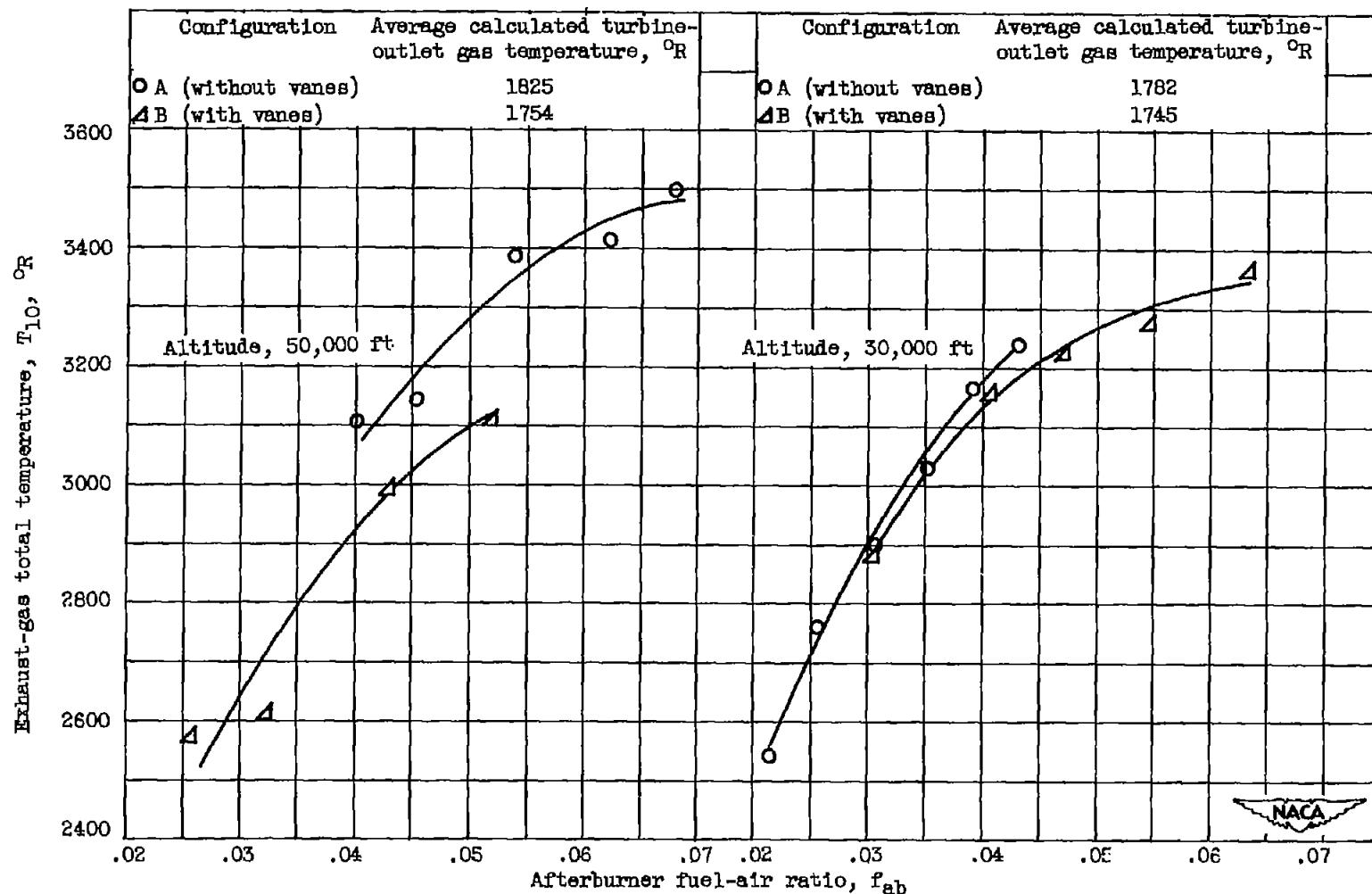


Figure 9 - Effect of turbine-outlet gas-straightening vanes, vortex generators, and corrugated liner on afterburner pressure loss. Flight Mach number, 0.6.



(a) Afterburner combustion efficiency (equivalent radial fuel distribution).

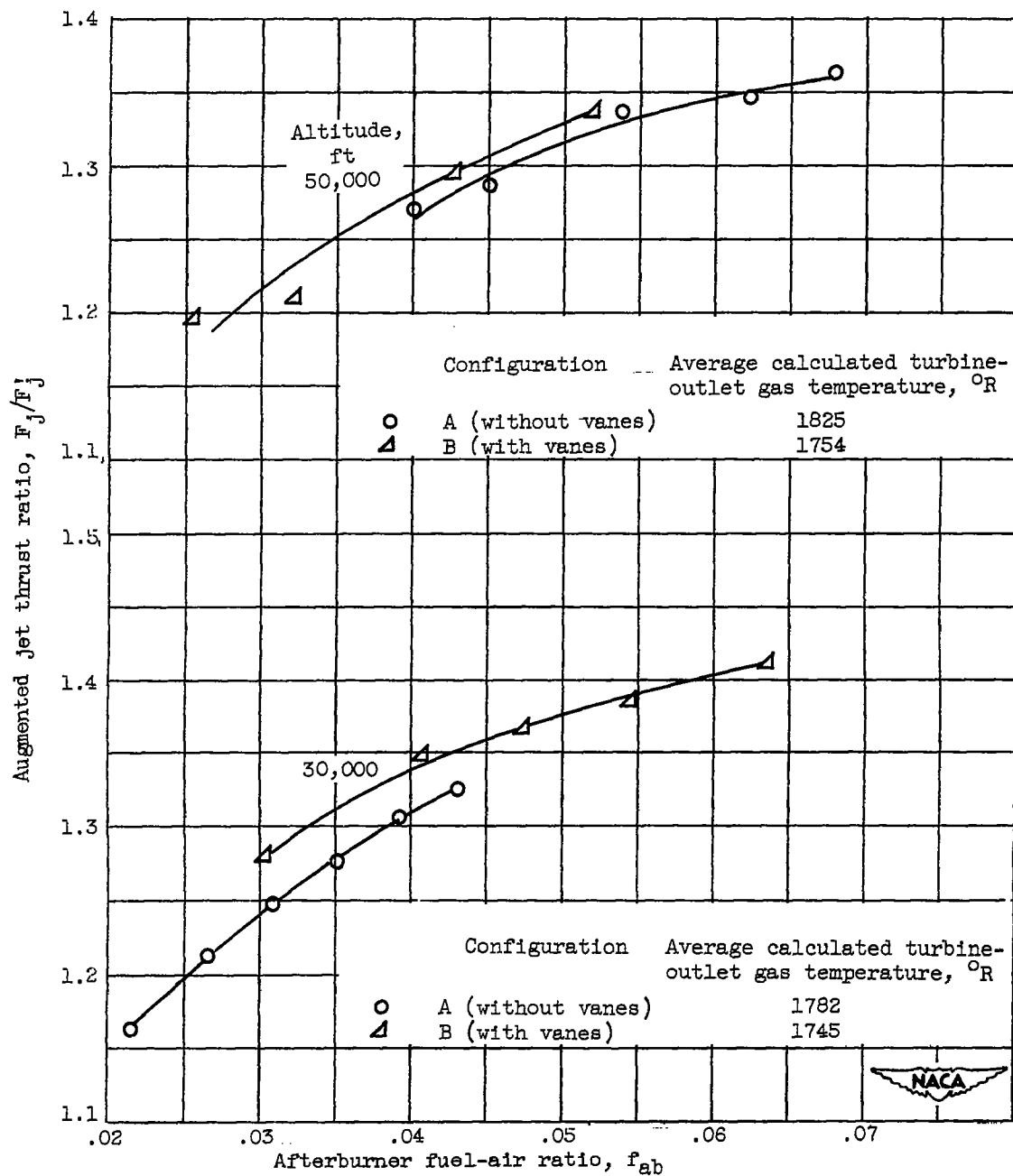
Figure 10. - Effect of turbine-outlet straightening vanes and vortex generators. Flight Mach number, 0.6.



(b) Exhaust-gas total temperature (equivalent radial fuel distribution).

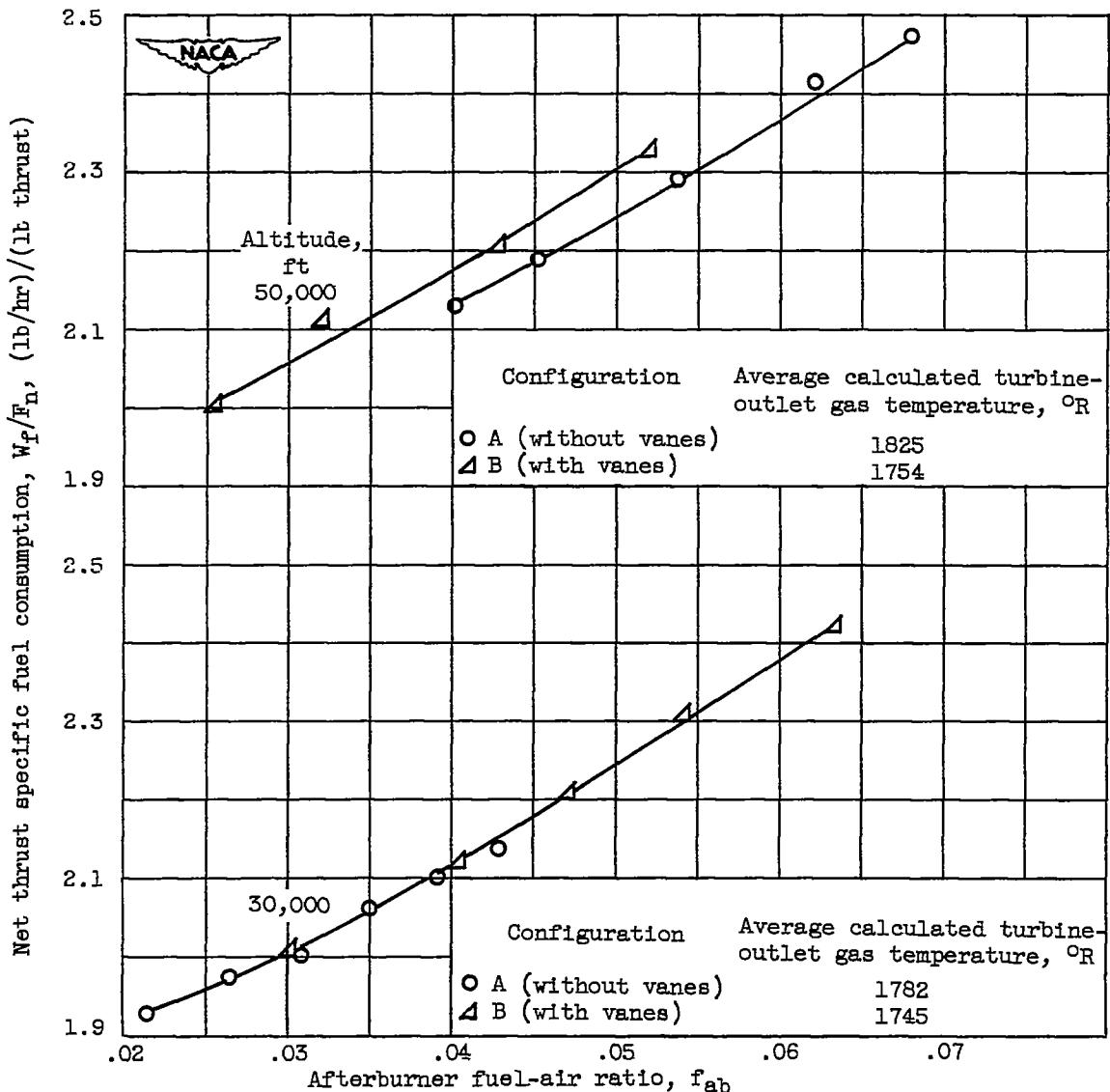
Figure 10. - Continued. Effect of turbine-outlet straightening vanes and vortex generators. Flight Mach number, 0.6.

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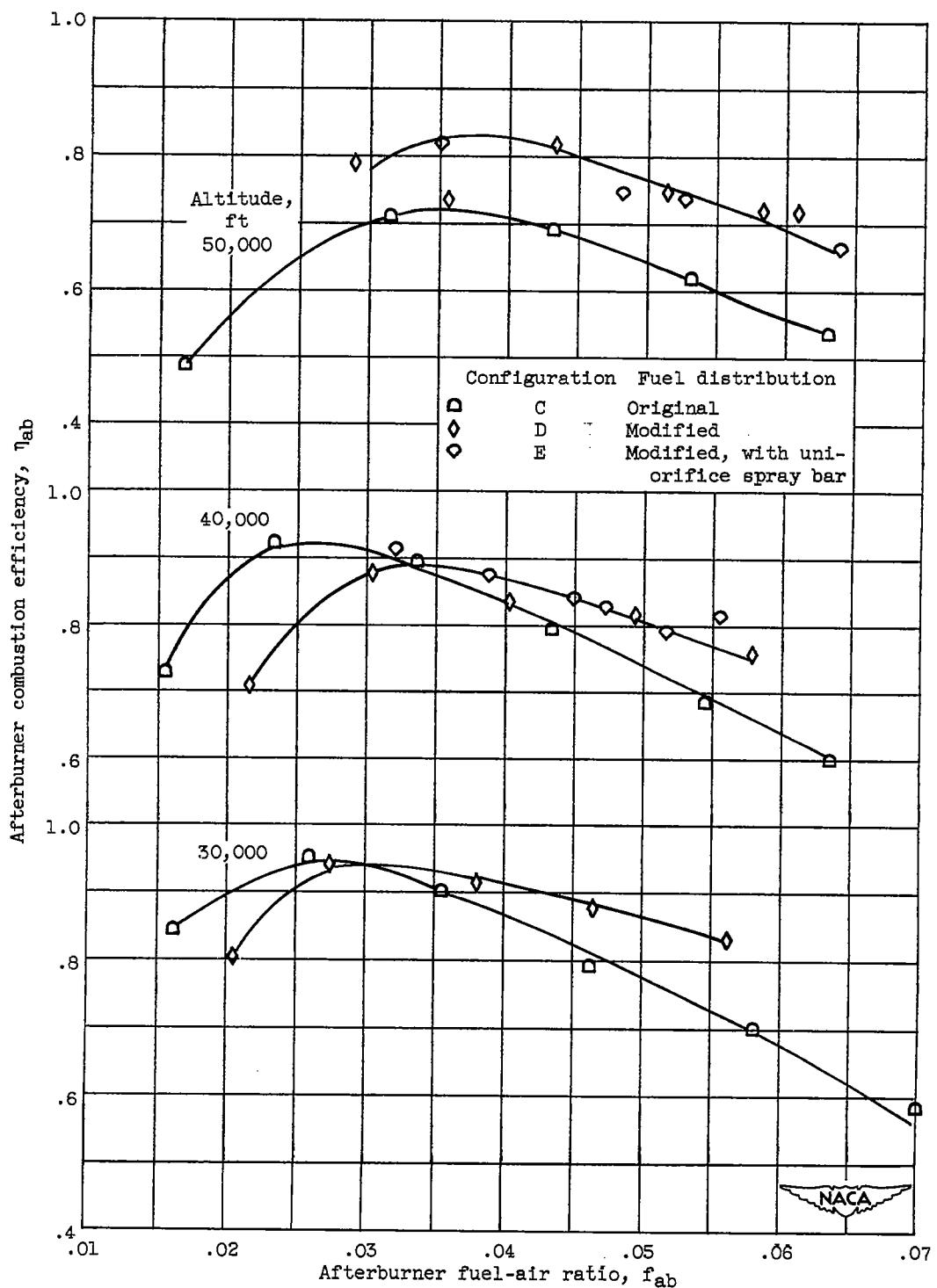
(c) Augmented jet thrust ratio (equivalent radial fuel distribution).

Figure 10. - Continued. Effect of turbine-outlet straightening vanes and vortex generators. Flight Mach number, 0.6.



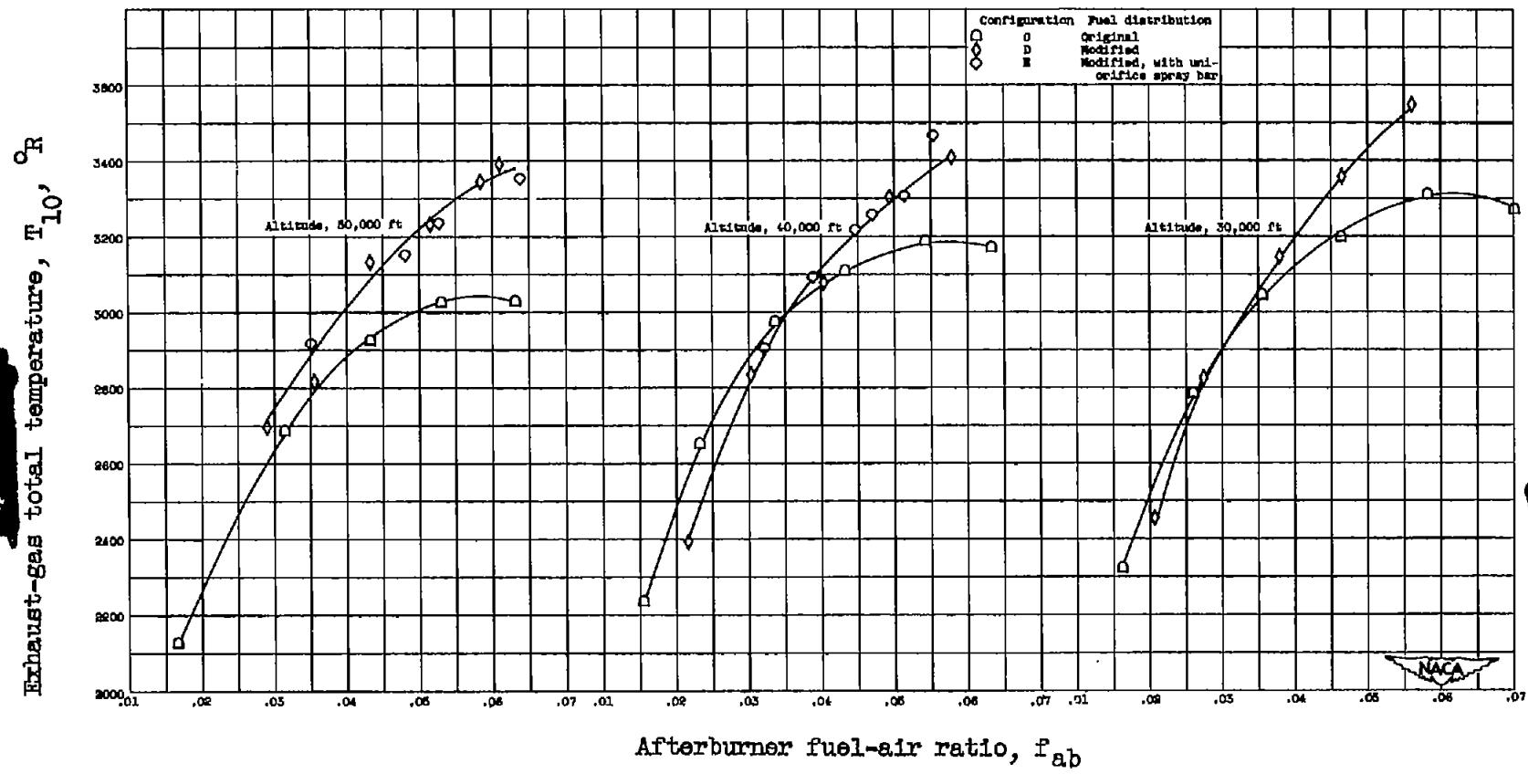
(d) Net thrust specific fuel consumption (equivalent radial fuel distribution).

Figure 10. - Concluded. Effect of turbine-outlet straightening vanes and vortex generators. Flight Mach number, 0.6.



(a) Afterburner combustion efficiency.

Figure 11. - Effect of fuel distribution. Flight Mach number, 0.6.



(b) Exhaust-gas total temperature.

Figure 11. - Continued. Effect of fuel distribution. Flight Mach number, 0.6.

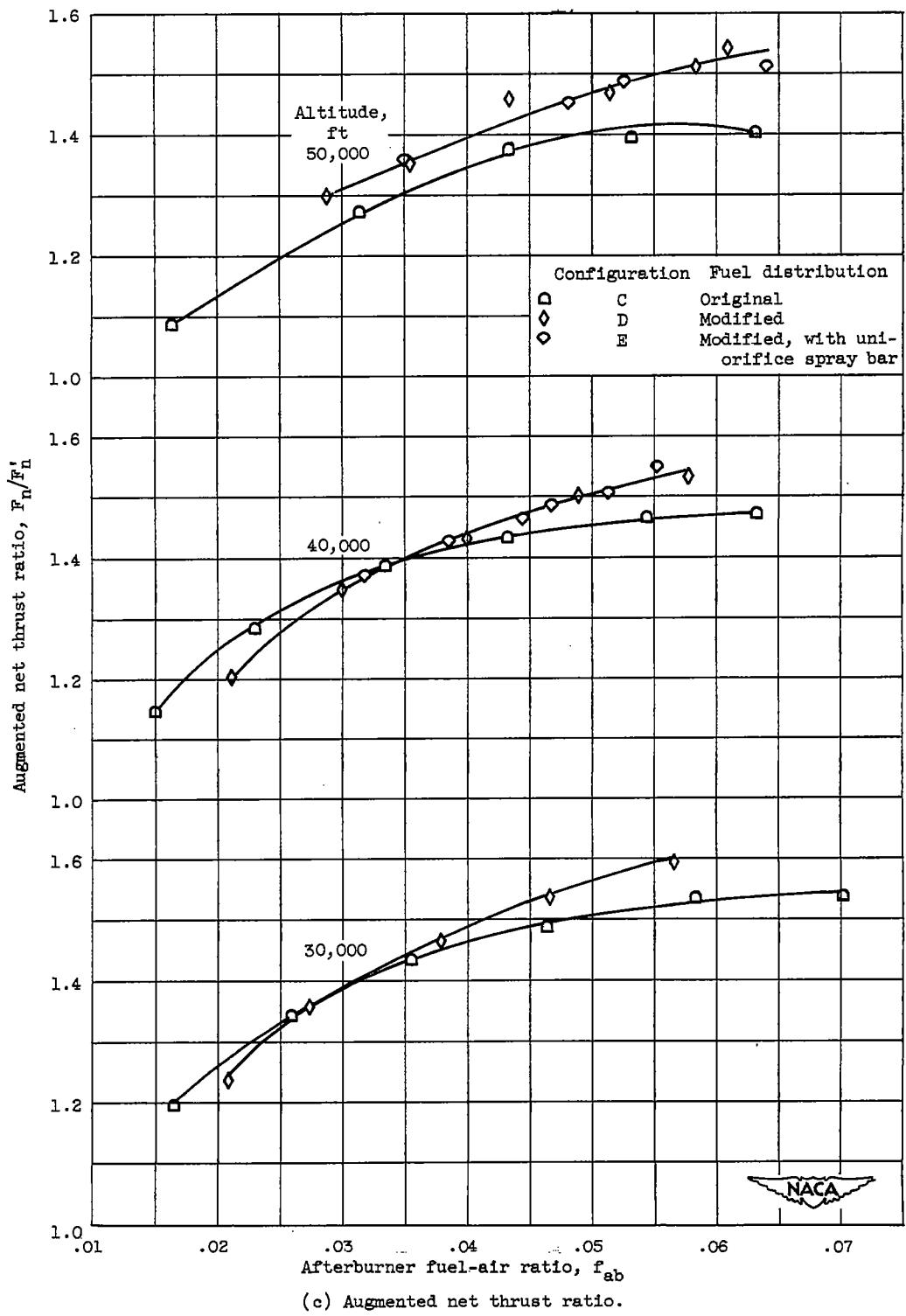


Figure 11. - Continued. Effect of fuel distribution. Flight Mach number, 0.6.

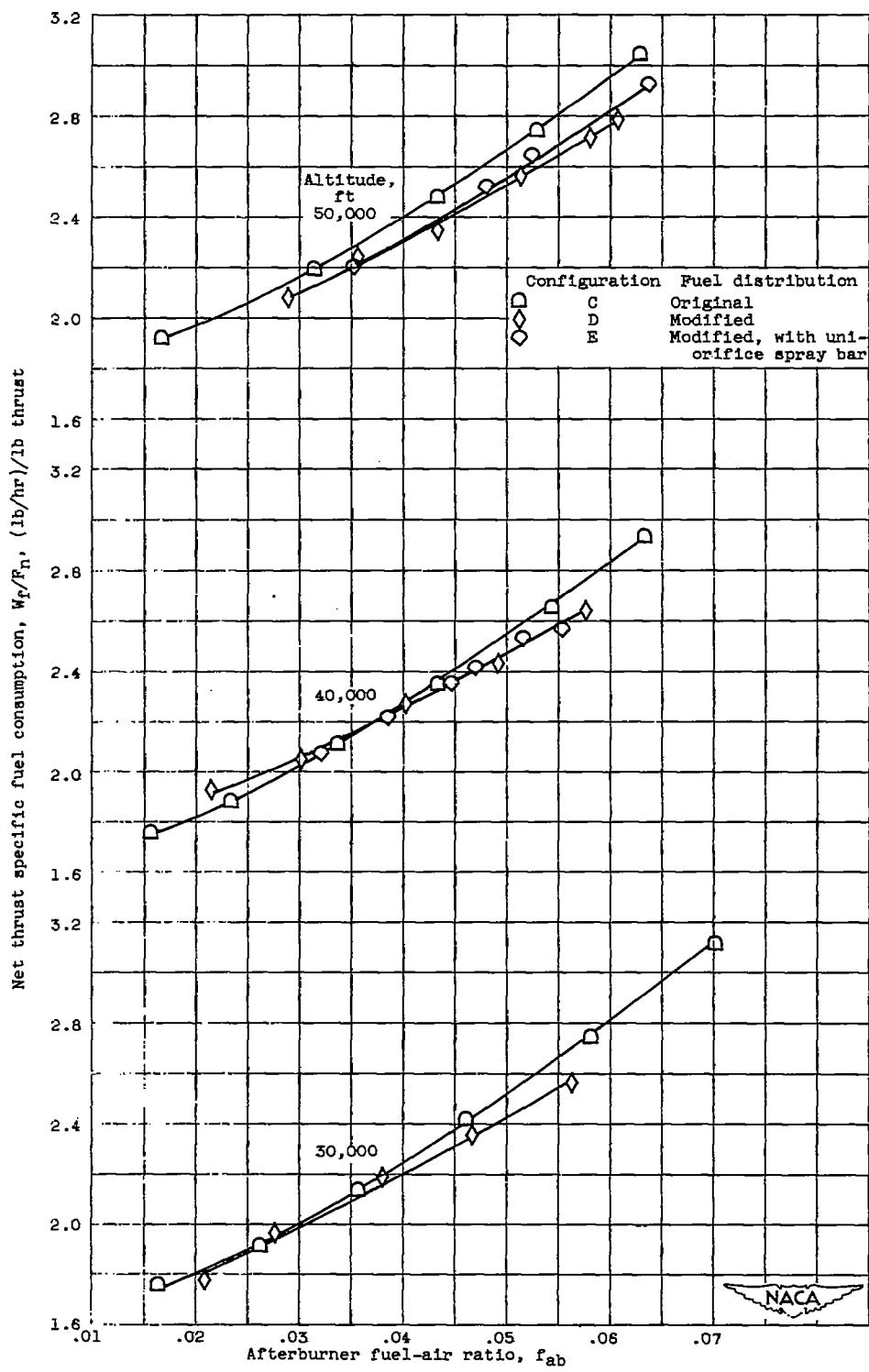


Figure 11. - Concluded. Effect of fuel distribution. Flight Mach number, 0.6.

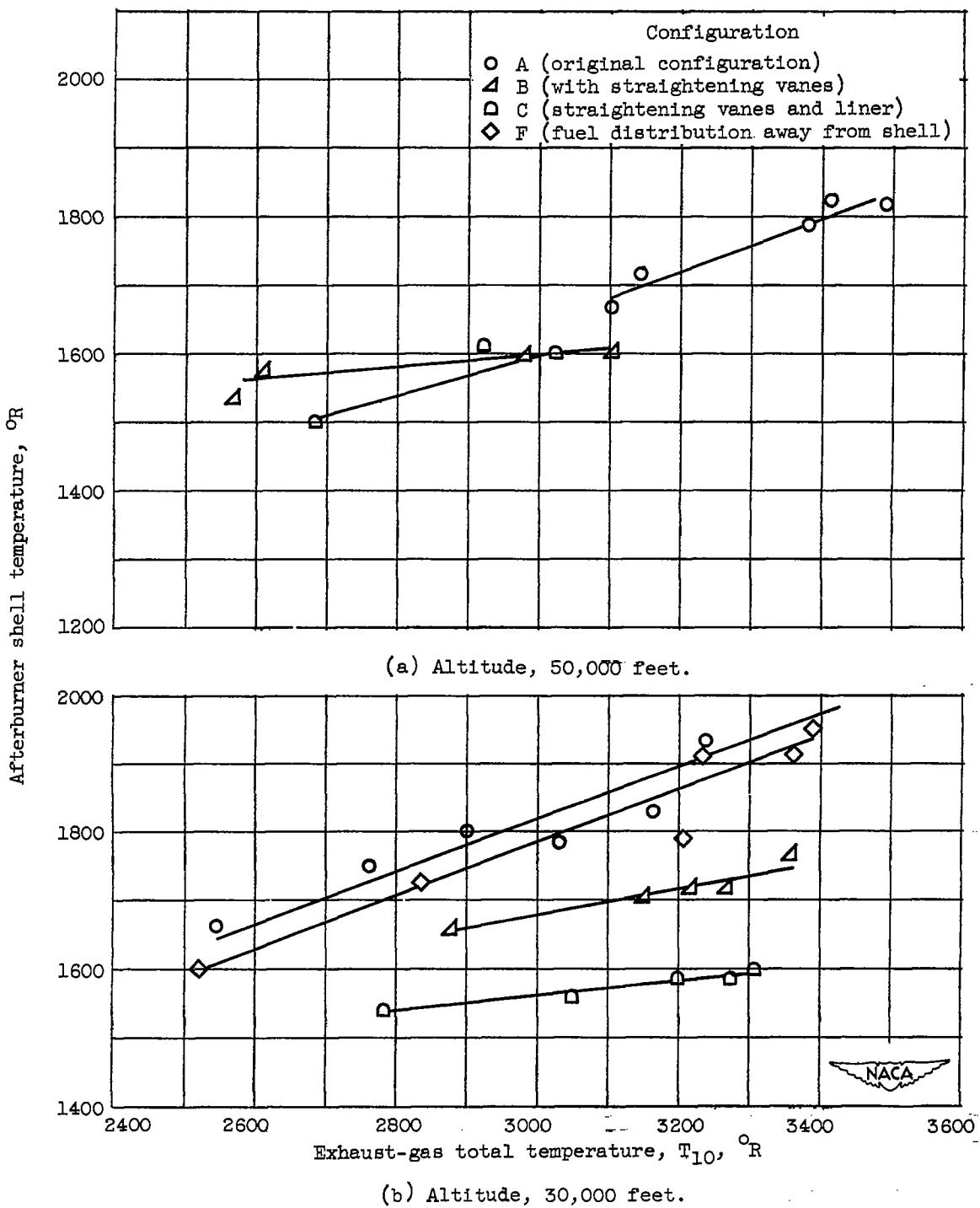


Figure 12. - Effect of turbine-outlet gas-straightening vanes and vortex generators, ceramic-coated corrugated liner, and fuel distribution on afterburner shell temperature. Flight Mach number, 0.6.

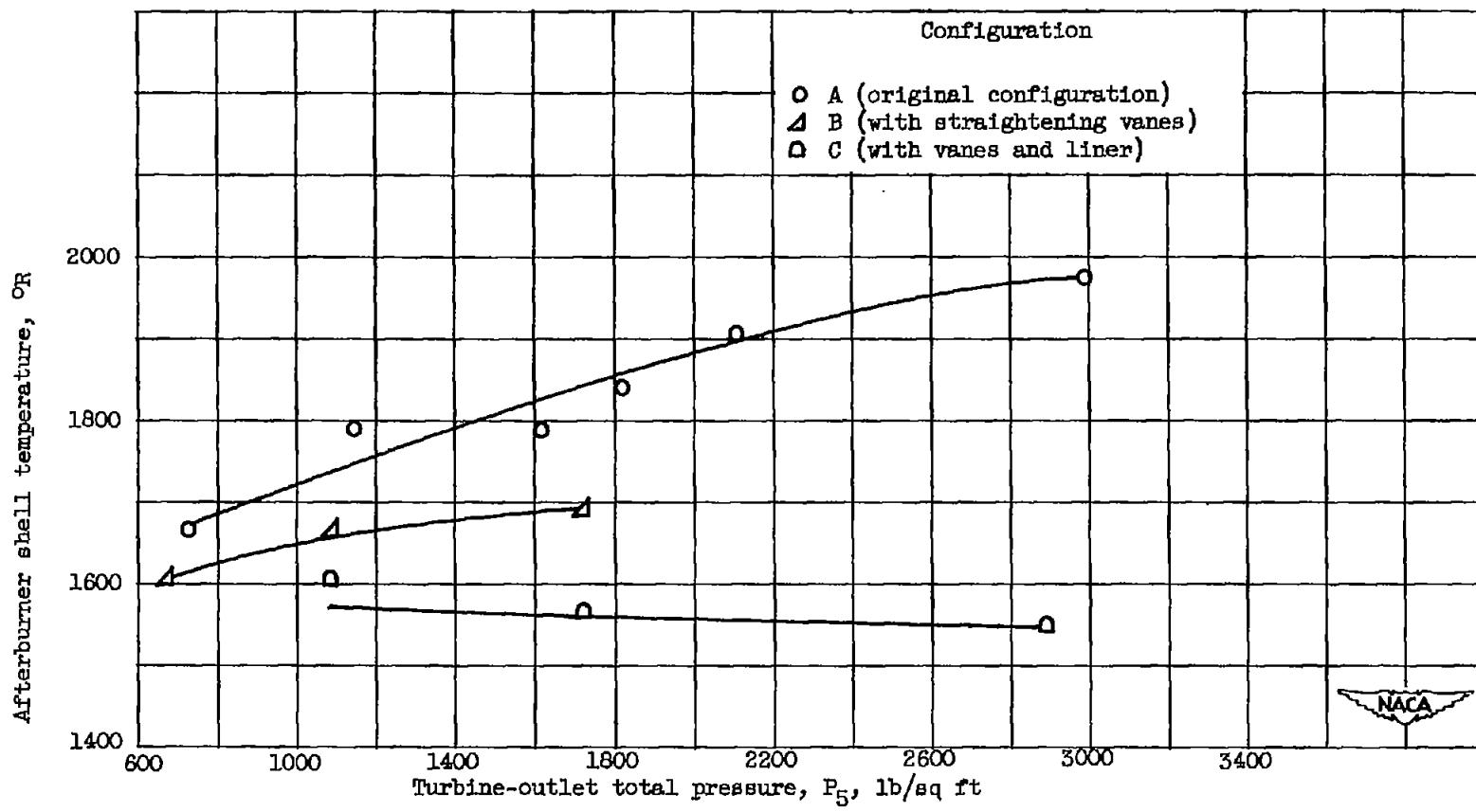


Figure 13. - Effect of turbine-outlet total pressure on afterburner shell temperature for gas temperature of 3100° R.

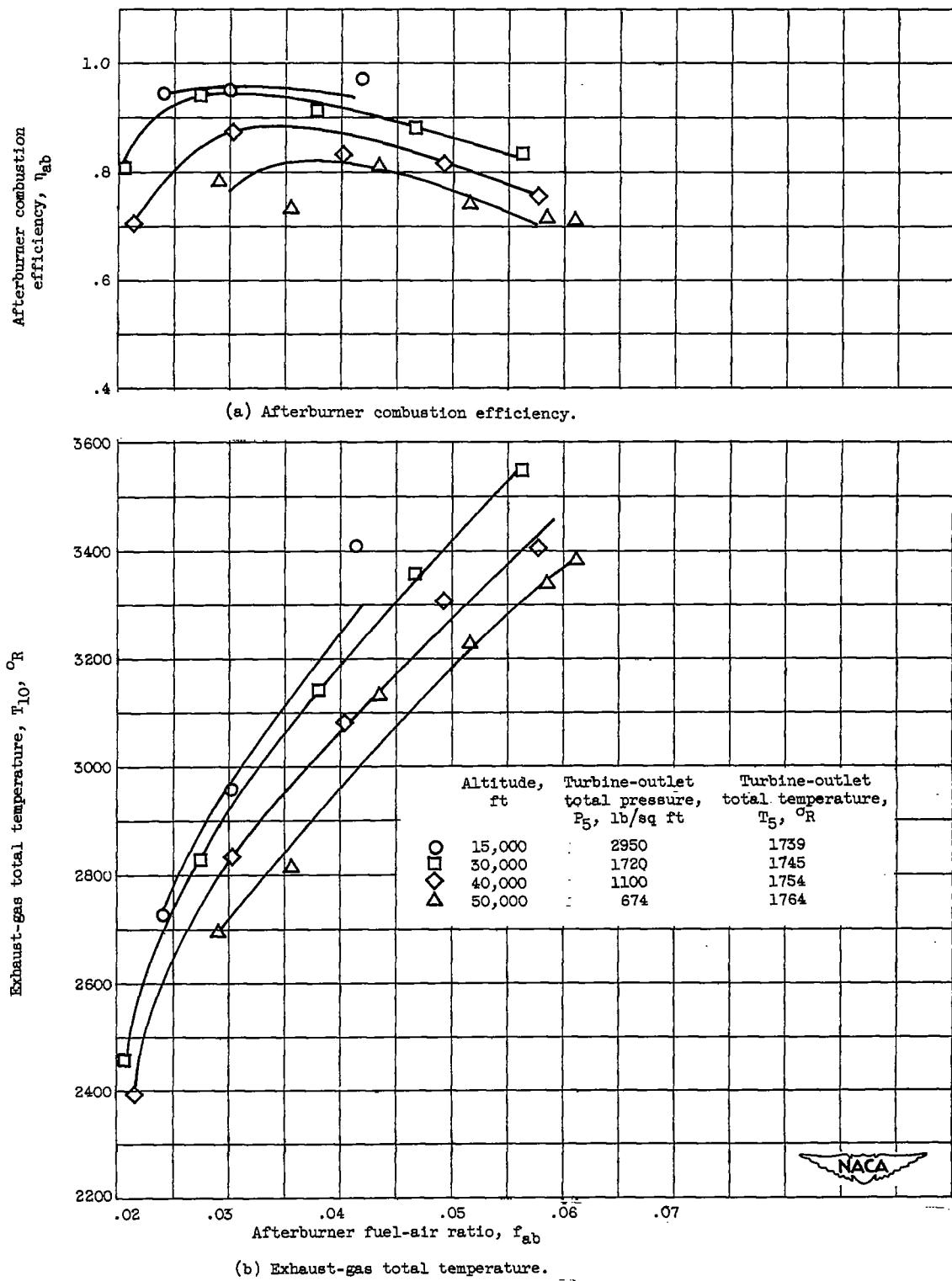


Figure 14.- Effect of altitude on performance of configuration D. Flight Mach number, 0.6.

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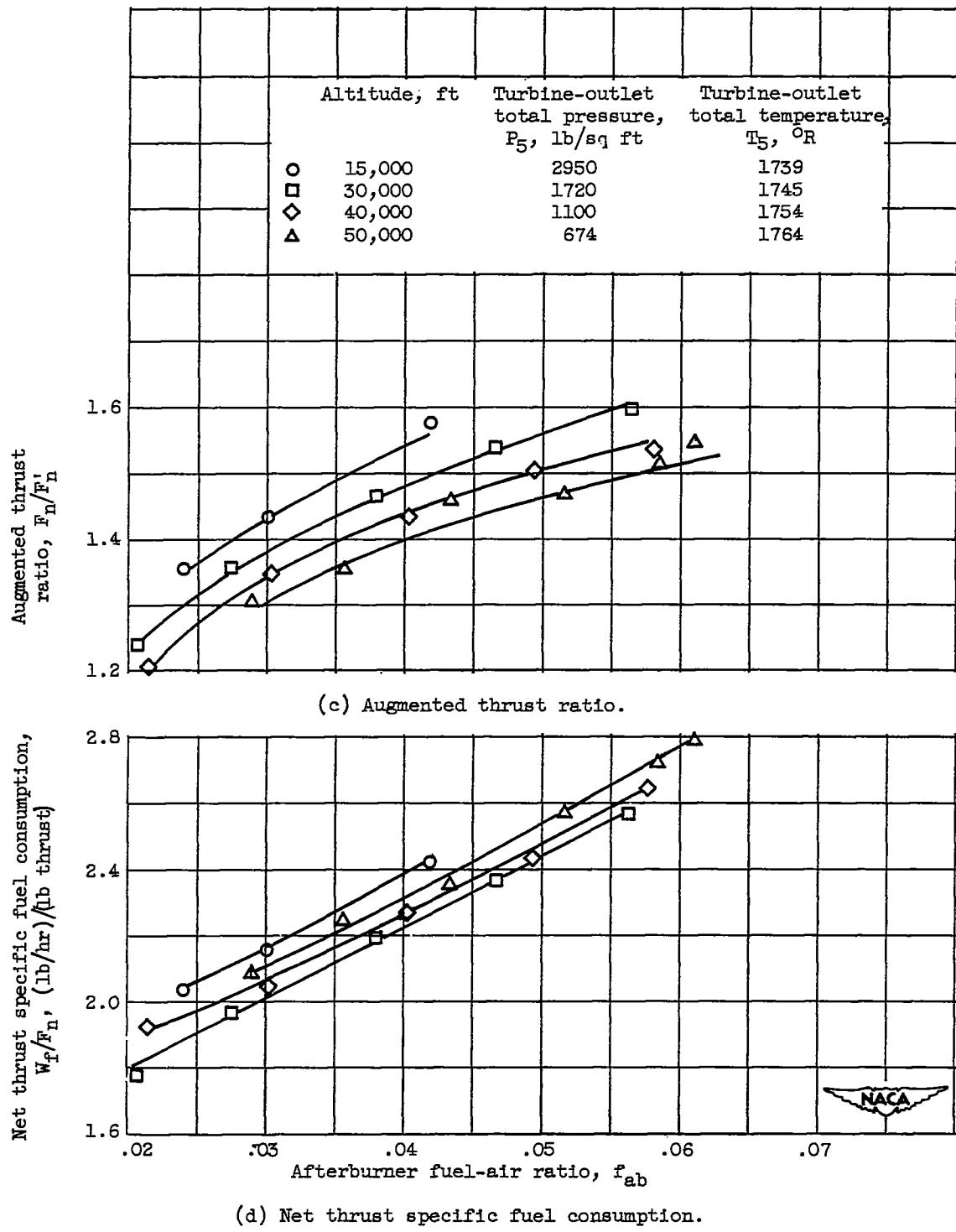


Figure 14. - Concluded. Effect of altitude on performance of configuration D. Flight Mach number, 0.6.

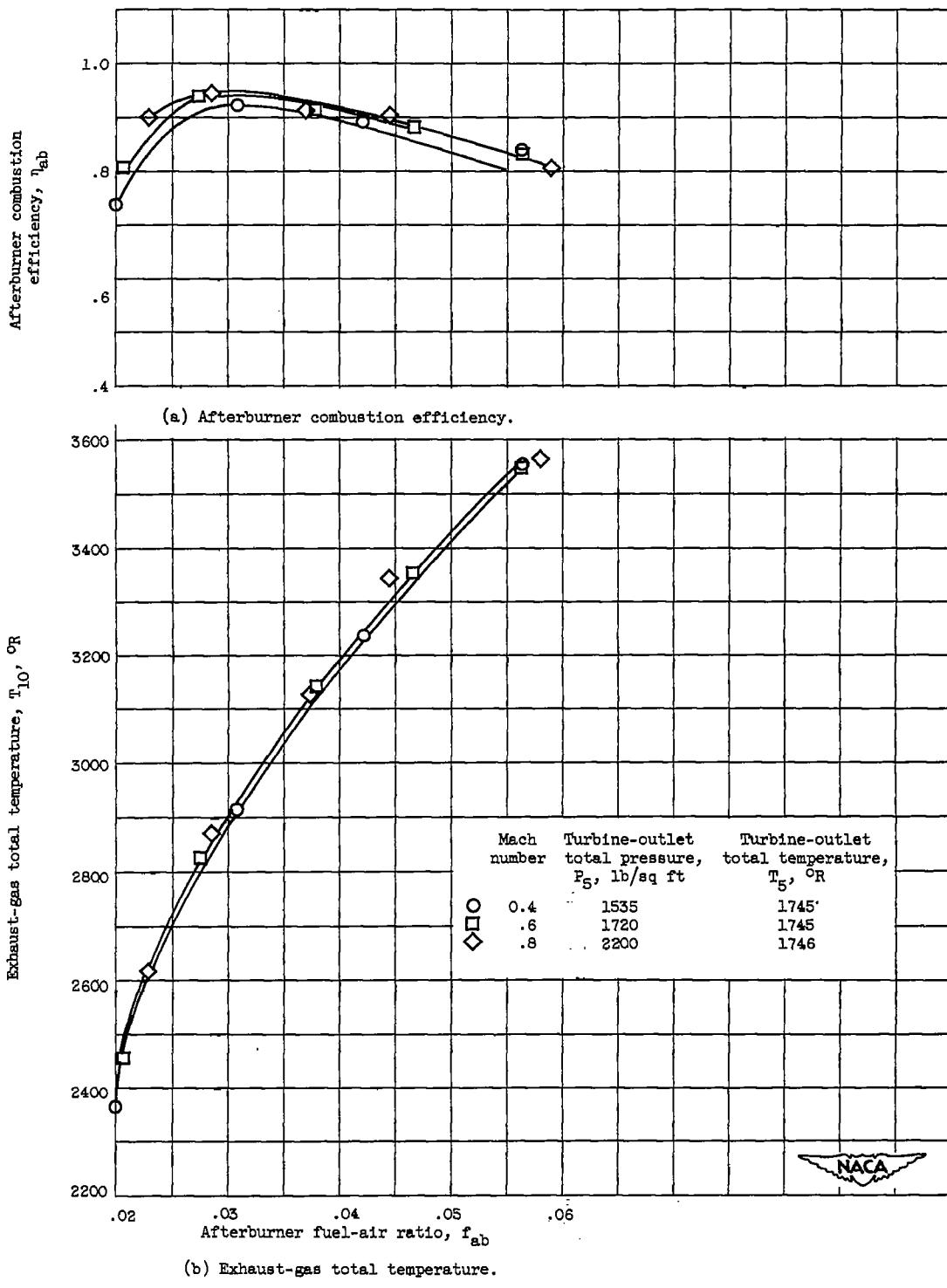


Figure 15. - Effect of flight Mach number on performance of configuration D.
Altitude, 30,000 feet.

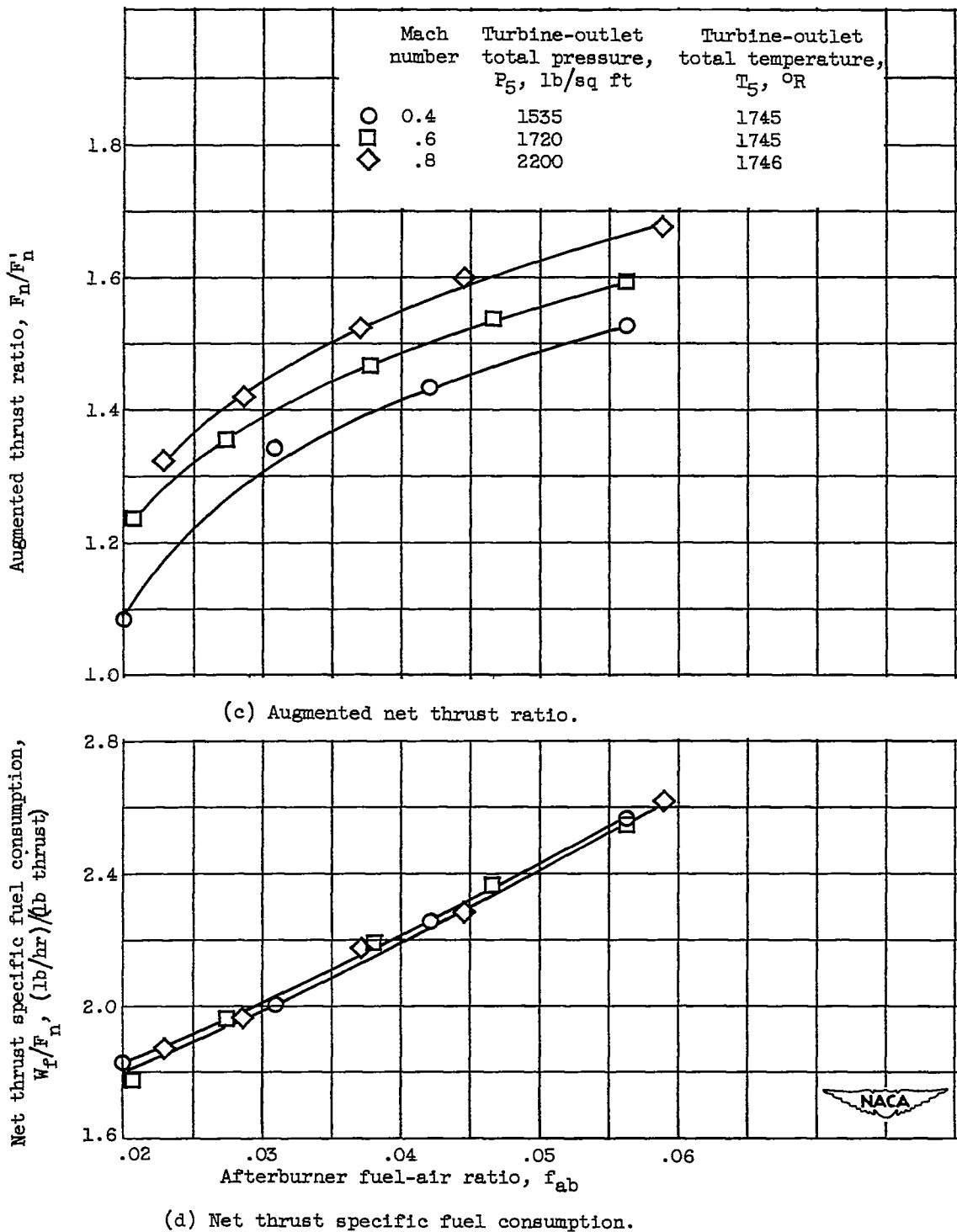


Figure 15. - Concluded. Effect of flight Mach number on performance of configuration D. Altitude, 30,000 feet.

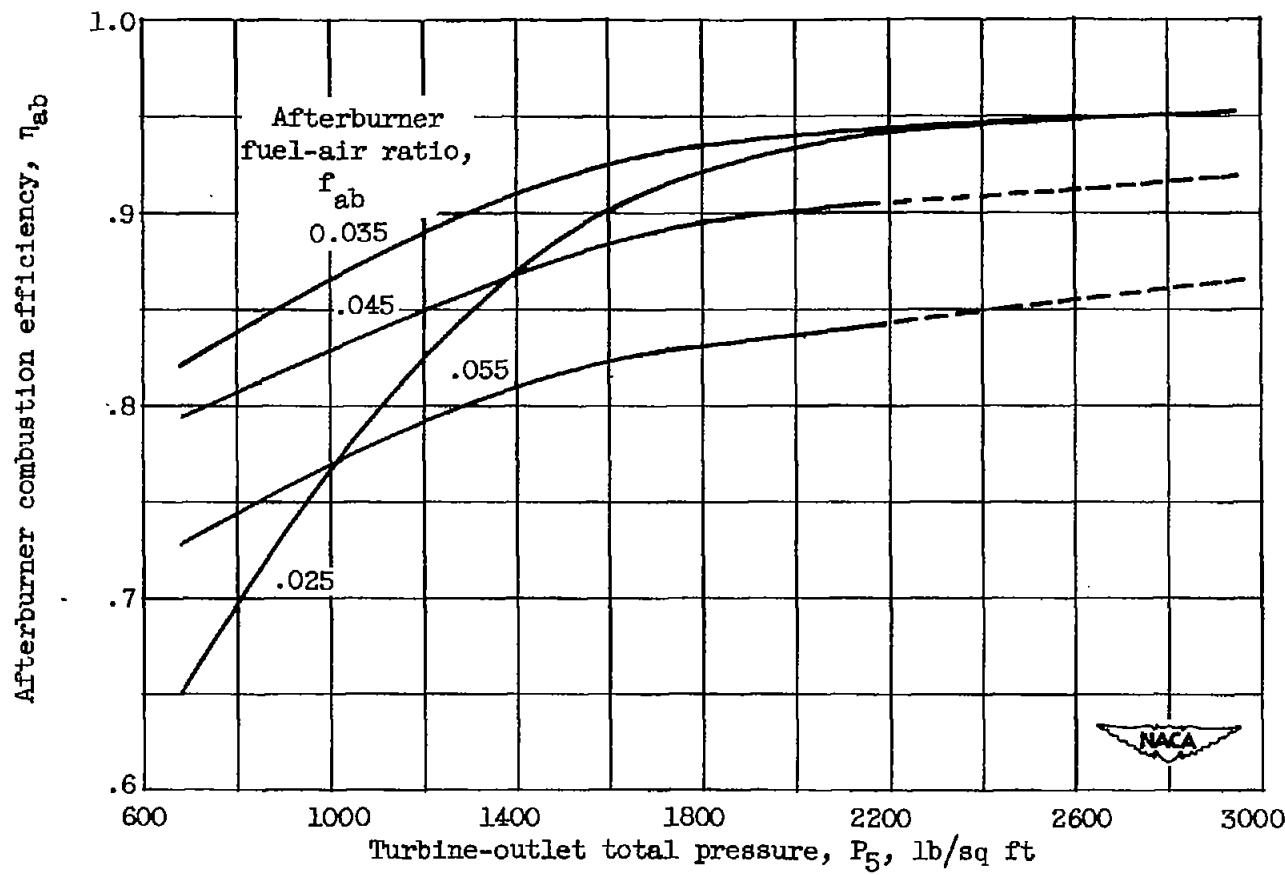
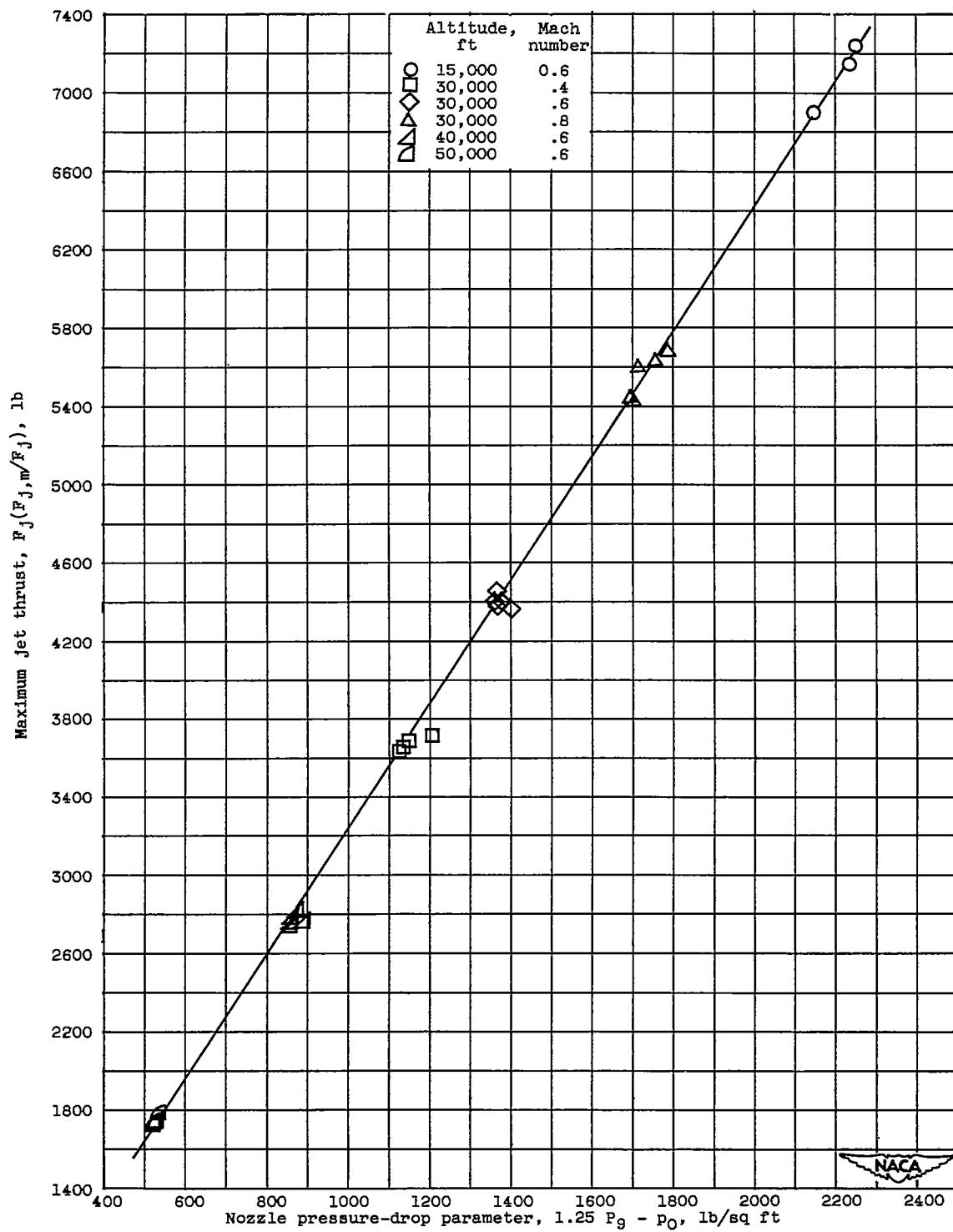
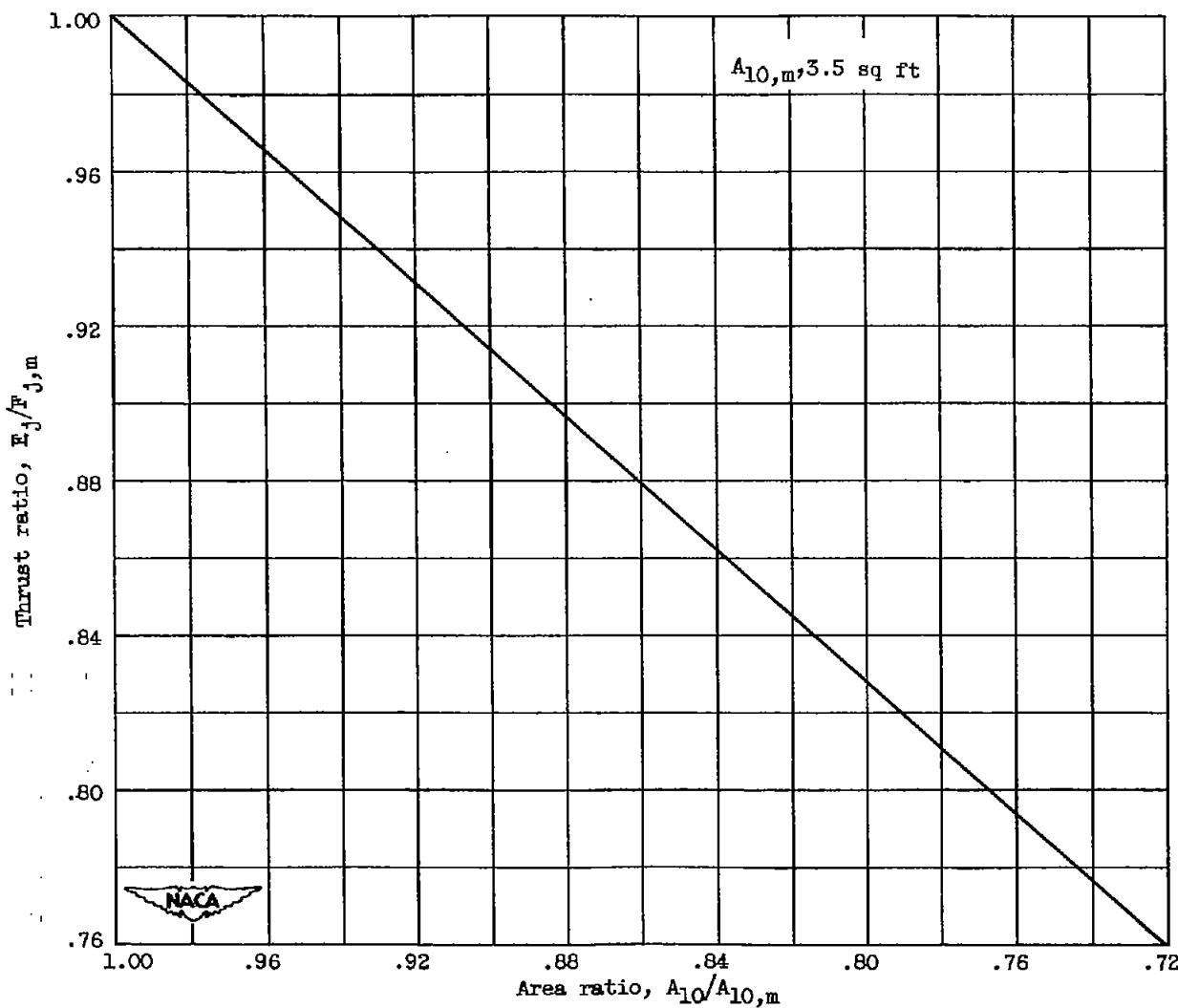


Figure 16. - Effect of turbine-outlet total pressure on combustion efficiency for various afterburner fuel-air ratios for configurations D and E.



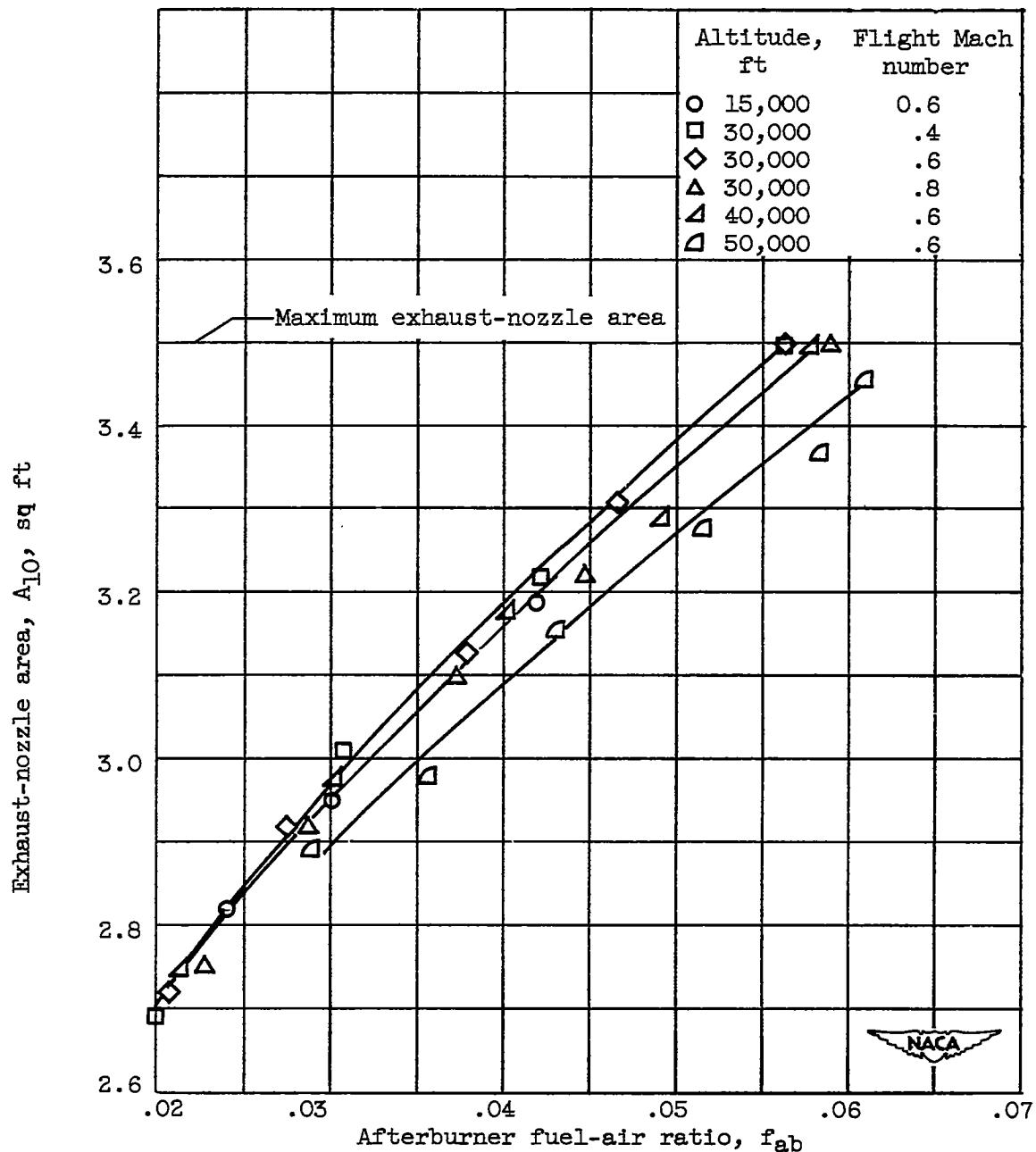
(a) Generalized jet thrust.

Figure 17. - Generalization of afterburning jet thrust for configuration D.



(b) Correction factor for jet thrust obtained from figure 17(a).

Figure 17. - Continued. Generalization of afterburning jet thrust for configuration D.



(c) Exhaust-nozzle area for various flight conditions.

Figure 17. - Concluded. Generalization of afterburning jet thrust for configuration D.